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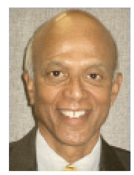

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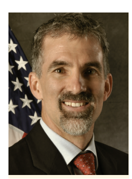

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Conference 10162: Bioinspiration, Biomimetics, and Bioreplication VII

SPIE. SMART STRUCTURES NDE

Sunday - Monday 26–27 March 2017

Part of Proceedings of SPIE Vol. 10162 Bioinspiration, Biomimetics, and Bioreplication 2017

10162-500, Session Plen

Plant nanobionic materials for thermally active, soft, artificial skins

Chiara Daraio, California Institute of Technology (United States)

No Abstract Available

10162-1, Session 1

Foldable drones: from biology to technology *(Invited Paper)*

Dario Floreano, Stefano Mintchev, Jun Shintake, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Current drones are developed with a fixed morphology that can limit their versatility and mission capabilities. There is biological evidence that adaptive morphological changes can not only extend dynamic performances, but also provide new functionalities.

For example, the trade-off between size and payload or flight endurance, can be addressed by foldable wings. Since lift force is proportional to the size of the drone, smaller drones suffered from significantly reduced time of flight and payload. This drawback can be overcome by incorporating foldable structures in relatively larger drone with suitable payload that can be stored and transported in a small volume [1-3].

Foldable wings can also enable the transition between aerial and ground locomotion, advancing the development of multi-modal drones with an extended mission envelope. Those include, for example, folding wing drones that can transition to a more compact shape suitable for crawling on the ground in cluttered environments [4,5].

The real potential of foldable drones is often limited by the use of conventional design strategies and rigid materials, which motivates to use smart, functional materials. Approaches to tackle this challenge are to develop structures that can become soft during morphing and stiff during regular operation by using origami structures [1,2] or variable stiffness materials [5]. These drones are actuated by smart materials such as electroactive polymers [6].

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10162-2, Session 1

A parametric study on a bio-inspired continuously morphing trailing edge

Amin Moosavian, Eun Jung Chae, Univ. of Michigan (United States); Alexander M. Pankonien, Air Force Research Lab. (United States); Daniel J. Inman, Univ. of Michigan (United States)

Inspired by the wave-like camber variation in the trailing edge feathers of large birds, the aerodynamic impact of similar variations in the geometry of morphing wings about a nominally constant flight condition is investigated. The scope of this problem is reduced by exploring parametrically generated geometries derived from an existing morphing wing design that mimics embedded bio-actuation, namely the Spanwise Morphing Trailing Edge (SMTE) actuated via conformally integrated Macro Fiber Composites (MFCs). Utilizing this design to generate smooth, single-parameter, chordwise variations in airfoil camber, the deformation of the trailing edge of the SMTE is also parameterized as a function of the spanwise location using a sinusoidal relationship. Maintaining a constant peak deviation of the trailing edge from the chord line, i.e. amplitude, the impact of varying two independent parameters, the spatial frequency, representing the total number of waves that could be formed along the wing span, and the phase shift, is investigated via Computational Fluid Dynamics (CFD) simulations, using the three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations with the k-? Shear Stress Transport (SST) turbulence model, thereby assessing the comparative impact on aerodynamic performance. Root forces and moments are used to gauge the overall aerodynamic efficiency while the moment measured about the effective hinge line is used to provide a surrogate for the required actuator energy. These factors are further elucidated by examining comparative pressure distributions.

10162-3, Session 1

Computational analysis of a flapping two different airfoils at laminar flow

Abduljaleel Altememe, Olivers J. Myers, Clemson Univ. (United States)

Selection of airfoil for better design of aerodynamic and aerodynamic performance is very important such as aircraft and wind turbine. Also, a number of military and civilian applications required efficient operation of airfoils in low Reynolds number. In this work, simulate a classical flow pattern (Von Karman Street) that can form as fluid flows past a flapping NACA0012 airfoil, and S1223 airfoil at low Reynolds number. These two airfoils has been selected and investigated in computational analysis by using multi-physics FEA. The S1223 airfoil, was selected in this paper for its high lift characteristics at low Reynolds number and the NACA0012 was chosen to check the lift at low Reynolds number. Velocity distributions are analyzed at different angles of attack for both airfoils. The results obtained from simulation have compared between the two airfoils. The results shows that, the values of lift of S1223 airfoil better than NACA 0012 at this regime. The magnitude and the frequencies of the oscillation generated by the fluid around the airfoils are computed and compared between the airfoils and compared with the values proposed by other researchers.

10162-4, Session 2

Can a robot grow? Plants give us the answer *(Invited Paper)*

Barbara Mazzolai, Andrea Degl"Innocenti, Istituto Italiano di Tecnologia (Italy)

Plants have a sessile lifestyle, and, as a consequence of this primordial decision, they must efficiently use the resources available in their surroundings and exhibit a well-organized sensing system that allows them to explore the environment and react rapidly to potentially dangerous circumstances. Below ground, roots can sense a multitude of abiotic and biotic signals, enabling the appropriate responses while they grow searching nutrients and water to feed the whole plant body. Plant roots show efficient exploration capabilities, adapting themselves morphologically to the environment to explore. Interestingly, movement, evolved sensing systems and distributed control are among the most important problems of contemporary robotics. Plants, which we have recently considered as a new model in bioinspired and soft robotics, must address "problems" that are common also in animals, such as, for example, squid, cuttlefish, and, especially, octopus, which include distributed control to manage the infinite degrees of freedom of their body, high flexibility, the capability of growing and/or elongating their extremities, and distributed sensing capabilities. Starting from the study and imitation of these plant features, we developed innovative inspired robots and technologies, named PLANTOIDS, which move by growing, coordinating their artificial roots and showing efficient penetration strategies and high actuation forces. Applications for such technologies include soil monitoring and exploration for contamination or mineral deposits, as well as medical and surgical applications, like new flexible endoscopes, able to steer and grow in delicate human organs.

10162-5, Session 2

Design and evaluation of a wasp-inspired steerable needle

Marta Scali, Davey Kreeft, Paul Breedveld, Dimitra Dodou, Technische Univ. Delft (Netherlands)

High accuracy and precision in reaching target locations inside the human body are necessary for the success of percutaneous procedures, such as biopsy and localized drug delivery. Flexible steerable needles may allow the surgeon to reach areas deep inside solid organs while avoiding sensitive structures (e.g., blood vessels). Needle steering can be achieved by means of a pre-defined needle shape, such as a bevel-tip, or by means of an actuator embedded in the needle body, such as cables or shape-memory alloy. Rotation around the longitudinal axis of a bevel-tip allows steering in multiple directions, but at a possible cost of tissue damage. Cables and other types of actuators allow steering to all directions, but they are often cumbersome, limiting the possibilities for miniaturization of the needle diameter. In nature, several species of parasitic wasps possess a thin and flexible ovipositor (i.e., an egg-laying device), which can be used as source of inspiration for developing thin steerable medical needles. The wasp is able to drill different kind of substrates and steer the ovipositor along curved trajectories. Inspired by the anatomy and the steering mechanism of the wasp ovipositor we designed and fabricated a multi-part needle prototype, in which each body part is actuated independently. Both straight and curved trajectories were tested in gelatine by varying the actuation sequence of the body parts. Preliminary experimental evaluation has shown that the prototype is able to follow both straight and curved paths without the need of rotation of the entire device.

10162-6, Session 2

Mosquito-inspired medical needles

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

The stinging proboscis in mosquitoes have diameters of only 40-100 ?m which are significantly smaller than the thinnest medical needles and the mechanics of these natural stinging mechanisms have therefore attracted attention. Studies of mosquito proboscis insertion have estimated that the lateral support of the fascicle provided by the labium increased the critical buckling load with a factor 5. These studies also showed, using a silicon micro-needle of the same size as the proboscis, that the insertion force could be reduced with 70% using vibration at a frequency around 200-400 Hz. The present paper gives an overview of the advanced set of mechanisms that allow the mosquito to penetrate human skin and presents results from experiments using biomimetic equivalents to the natural mechanisms. This includes supporting sheet, vibration, micro-barbs for reduced friction and skin stretching. The buckling strength is shown to increase with a factor 3.5 using FEM-software and laboratory tests. The paper will also present other biological mechanisms that facilitate skin penetration. The work aims at improving the skin penetrating properties for polymer needles.

10162-7, Session 2

Eco-friendly fabrication of nanostructured porous silicon from accumulator plants: morphological control and drug delivery *(Invited Paper)*

Jhansi Kalluri, Nguyen T. Le, Texas Christian Univ. (United States); Armando Loni, pSiMedica Ltd. (United Kingdom); Leigh T. Canham, pSiMedica Ltd. (United Kingdom) and The Univ. of Birmingham (United Kingdom); Jeffrey L. Coffer, Texas Christian Univ. (United States)

Silicon(Si), in nanostructured mesoporous form, is attracting extensive attention in biomedically-relevant applications such as biosensing, drug delivery, and tissue engineering. The use of electronic grade silicon as a feedstock for porous Si production has economic obstacles to high volume applications, and requires significant amounts of corrosive reagents such as hydrofluoric acid.

As an alternative, we have developed a cost-effective, eco-friendly fabrication method that involves the chemical extraction of silica from silicon accumulator plants followed by a magnesiothermic reduction into porous silicon.

In this presentation we focus on two complementary issues. The first entails an investigation of the influence of specific plant component on the morphology of the resultant porous silicon. This is investigated for the case of Equisetum telmateia (Giant Horsetail), where we have detected a very different pSi morphology in the stem-derived material (hierarchical macro to mesoporous form) than from the pSi derived from the fronds, which is limited to mesopores only.

The second item discussed here is the ability of plant-derived porous silicon to stabilize and ultimately deliver metastable therapeutic species. We describe several examples of the incorporation and properties of both natural product-derived antibacterial agents as well as useful photo/thermal-sensitive vitamins into plant-derived pSi derived from Tabasheer powder, a silicon-accumulating species from the nodal joints of the Bambuseae plant.

The studies presented here demonstrate that plant-derived pSi can act as a carrier for the controlled release of multiple therapeutics. Such studies should expand the appeal of this low-cost, naturally-derived nanostructured matrix in higher volume applications.

10162-8, Session 2

Liposomes: bio-inspired containers for physically triggered drug delivery

Sofiya Matviykiv, Marzia Buscema, Thomas Pfohl, Univ. Basel (Switzerland); Andreas Zumbühl, Univ. de Fribourg (Switzerland); Bert Müller, Univ. Basel (Switzerland)

For natural scientists and engineers, learning from nature has long being a source of bio-inspiration. For example, engineers have designed multifunctional materials with a hierarchical structure. Lipid bilayers, the principal components of cell membranes, can easily be arranged as spheres, i.e. forming liposomes. Such liposomes might not be recognized by the human body as foreign antigens and thus could serve as containers for targeted drug delivery. Our team has developed a promising approach building non-spherical, mechano-sensitive liposomes about 100 nm in diameter [1]. This bio-inspired strategy of mechanically triggered release of, for example, a vasodilator to widen constricted arteries, offers a wide range of applications. In particular, the targeted release at critically stenosed arteries (as a result of atherosclerosis) significantly reduces the undesired side effects such as a reduced blood pressure and will allow higher local dosage. Currently, such liposomes can be constructed from artificially synthetized Pad-PC-Pad (1,3-palmitoylamido-1,3-deoxy-sn-glycero-2-phosphatidyl-choline) [1]. It is well known that liposomal drugs, even currently on the market (e.g. Doxil), often induce adverse immune responses [2]. Therefore, we have performed in vitro complement activation experiments and related animal studies with pigs [3]. We could demonstrate that bare and nitroglycerin-loaded Pad-PC-Pad liposomes exhibit a surprisingly low complement activation even for dosages much higher than for the systemic administration of FDA-approved liposomal drugs. Furthermore, the liposomal suspensions applied are stable for a period of more than two months. In summary, non-spherical Pad-PC-Pad liposomes of nanometer size are promising containers for physically triggered drug delivery.

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10162-9, Session 3

Utilizing concepts of mechanics, transport, and assembly in nature: towards responsive materials *(Invited Paper)*

LaShanda Korley, Symone Alexander, Alex Jordan, Case Western Reserve Univ. (United States)

Taking clues from nature, we are interested in understanding the design rules employed by nature and applying these strategies to the development of mechanically-enhanced and tunable materials. Fiber constructs are prevalent in natural systems, from collagen fiber networks in tendon to tough spider silk fibers. With these bio-inspired cues, we are intrigued by the impact of synthetic fiber orientation, alignment, manufacturing, and reinforcement on mechanics and functionality.

Recent innovations in multilayer co-extrusion technology have translated to the fabrication of melt-extruded polymeric rectangular fiber mats and composites. Distinct advantages of this modular approach over other traditional fiber processing techniques include scalability, environmentally-friendly conditions, and the ability to obtain cross-sectional dimensions on the nanoscale. Here, we describe the mechanics and structural features of biologically-relevant, high surface area fiber mats. Functional fiber substrates were obtained via facile surface modification and inclusion of therapeutics. We also focus on this fiber technology as a new platform for the development of reinforced hydrogels via an in situ approach. This manufacturing strategy allows for strategic control of hydrogel architecture, fiber alignment and loading, compressive stability and stiffness. Promising results related to cell adherence and growth as well as therapeutic delivery are highlighted for these extruded hydrogel scaffolds.

Beyond fiber manufacturing, we are also interested in the fabrication of responsive composite systems utilizing high modulus, electrospun and low molecular gelators as fillers. Here, we discuss new insights into hygromorphic response in composites utilizing concepts of interfacial assembly, transport, bias, and orientation. These water-responsive systems may have unique applications in therapeutic delivery and chemical/biological protection.

10162-10, Session 3

Improving the properties of Kevlar through atomic layer deposition

Mato Knez, Itxasne Azpitarte, CIC nanoGUNE Consolider (Spain)

Polyaramides, such as Kevlar®, are of great technological importance for their extraordinary mechanical performance. Kevlar fibers are used in personal safety, for reinforcement of tires and ropes, and in further material composites that require extreme mechanical stability. The origin of the mechanical robustness of Kevlar lies in the alignment on the molecular level and the intermolecular interactions of the constituting amides. The properties of the polymer are dependent on the environmental conditions. Similar to proteins, elevated temperatures and/or irradiation with UV light lower the performance of the aramide.

Nature shows an efficient way to reinforce biopolymers from the mechanical point of view. This natural way is based on incorporation of metal ions into the protein structure, which results in enhancement of the inter- or intramolecular bonding. Soft structures can thus be turned hard or vice versa by simply controlling the presence and amount of metal ions inside the biopolymer.

In our approach we apply solvent free vapor phase infiltration techniques for impregnating polyaramides with metal ions or metal oxides with the purpose of achieving extraordinary physical properties. We will show that the procedure is the method-of-choice for stabilizing the thermal sensitivity of Kevlar while at the same time introducing protection against UV-induced degradation and further properties which such polymers intrinsically do not possess.

10162-11, Session 3

Biomimetic reactions in conducting polymers for artificial muscles: sensing working conditions

Victor H. Pascual, Toribio Fernández Otero, Univ. Politécnica de Cartagena (Spain); Johanna Schumacher, Arquimea Ingeniería, S.L.U. (Spain)

In the dense gel that is the intracellular matrix forming part of living cells electrochemical reactions take place provoking the interchange of ions and water with the surroundings. Systems containing conducting polymers mimic this feature of biological organs. In particular, conducting polymers are being studied as dual sensing-actuating reactive materials giving new multifunctional sensing-actuators, which allow the construction and theoretical description of artificial proprioceptive devices. Here films of polypyrrole/dodecyl benzene sulfonate (PPy-DBS) coating a platinum electrode were submitted to potential sweeps at different sweep rates in order to explore if the polymer reaction senses the working electrochemical conditions. The effective consumed electrical energy per cycle follows a

fast decrease when the scan rate increases described by the addition of two exponential sensing functions. Moreover, the variation of the hysteresis from the parallel charge/potential loop with the scan rate is also described by the addition of two exponential functions. In both cases the exponential functions fitting results at low scan rates are related to reaction-driven conformational movements of the polymer chains, being closer to biochemical conformational and allosteric sensors. The second exponential functions fitting results at high scan rates are related to diffusion kinetic control, being closer to present electrochemical sensors.

10162-12, Session 3

Stretchable artificial muscles for soft robotic applications

Geoffrey M. Spinks, Univ. of Wollongong (Australia)

Soft robots are being developed to mimic the movement of biological organisms and as wearable garments to assist human movement in rehabilitation, training, and tasks encountered in functional daily living. Stretchable artificial muscles are well suited as the active mechanical element in soft wearable robotics and here the performance of highly stretchable and compliant polymer coil muscles are described and analysed. The force and displacements generated by a given stimulus are shown to be determined by the external loading conditions and the main material properties of free stroke and stiffness. Spring mechanics and a model based on a single helix are used to evaluate both the coil stiffness and the mechanism of coil actuation. The latter is directly coupled to a torsional actuation in the twisted fiber that forms the coil. The single helix model illustrates how fiber volume changes generate a partial fiber untwist and spring mechanics shows how this fiber untwist generates large tensile strokes and high gravimetric work outputs in the polymer coil muscles. These analyses highlight possible as yet unexplored means for further enhancing the performance of these systems.

10162-13, Session 3

Bio-inspired research in dentistry

Bert Müller, Ali Akzorba, Fabien Bornert, Bernd Ilgenstein, Kurt Jäger, Georg Schulz, Hans Deyhle, Univ. Basel (Switzerland)

Crowns of human teeth consist of a unique, biologically ordered material with hydroxyapatite crystallites and collagen fibers. In the human cavity, they may remain functionally stable for many decades. The crowns of human teeth have even been known to last for millennia being a valuable report of the past. No engineering process is known to reproduce, for example, human crown enamel. Attacks by acidogenic bacteria, however, generally lead to dissolution and cavitation. Dental caries is stated to be the most prevalent chronic childhood disease worldwide. It is the primary cause of oral pain and tooth loss. The burden of dental caries lasts a lifetime, because once the tooth structure is destroyed, it will usually need restoration and additional maintenance throughout life. In addition, the economic impact of such therapeutic approaches is enormous. The World Health Organization estimated that dental treatment costs accounted for 5 % to 10 % of healthcare budgets in industrialized countries. So far, treatments have relied mainly on the mechanical replacement of decayed tissue by inert biomaterials, including isotropic polymers or composite materials. We present a detailed hard X-ray characterization study of crowns of human teeth covering the morphology from the entire subject via micro- down to the nanostructure. This analysis will support the development of strategies to repair the crowns in biomimetic manner and by means of nanotechnology. Currently, only small lesions, termed white spots, can be successfully treated. Therefore, our team wants to boost the efforts in developing methods to investigate the bio-inspired mineralization of enamel and dentin lesions.

10162-14, Session 3

MEMS scale active artificial hair cell sensors inspired by the cochlear amplifier effect

Sheyda Davaria, Pablo A. Tarazaga, Virginia Polytechnic Institute and State Univ. (United States)

Research over the past few decades has shown that the ear exhibits an important, nonlinear amplification called the “cochlear amplification.” It is responsible for boosting vibrations due to faint sounds and improving frequency sensitivity, which allows the ear to process a larger range of sound intensities (from about 20 micro-Pa to 20 Pa). In contrast, typical microphones, accelerometers, and other dynamic sensors are designed to operate linearly in the sensor’s quasistatic response region. Instead, the cochlea operates in the resonance region, where weak inputs are significantly amplified. The goal of our research is to develop unique, piezoelectric-based MEMS sensors that mimic the nonlinear amplification observed in the mammalian cochlea. Inspired by the stereocilia geometry of the hair cells, a set of active artificial hair cells (AHCs) are designed based on piezoelectric (PZT) cantilever beams.

The design consists of a passive substrate material and a layer of PZT deposition that imitates the amplification functions of the outer hair cells. By examining models of the biological cochlea, a nonlinear feedback control law is developed which applies the appropriate forcing conditions to the beam to amplify vibration initially induced by an external stimulus. Developing piezoelectric, active AHCs capable of mimicking the cochlea’s nonlinear behavior is the main scope of this work. A series of dynamic tests are conducted in order measure the response of the MEMS sensors with or without the control law.

10162-15, Session 3

Synthesis of biomimetic microparticles

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

Pollen are extremely durable ‘containers’ to transport DNA from anther to pistil in flowering plants. Here, we aim at mimicking the formation and surface structuring of such particles by using the polycondensation of dianhydrides and diamines to form polyimides. Depending on the solvent and reaction conditions, nanostructured surface coating can be obtained.

10162-16, Session 4

A thin polymer membrane ‘NanoSuit’ allows living organisms to survive in the harsh conditions of electron microscopy *(Invited Paper)*

Takahiko Hariyama, Hamamatsu Univ. School of Medicine (Japan)

Although extremely useful for a wide range of investigations, electron microscopy (EM) has until recently not allowed researchers to observe living organisms. However, we have reported previously that a simple surface modification consisting of a thin extra layer, coined “NanoSuit®” by us, kept organisms alive in the high vacuum (10-3-10-7 Pa). We found that the NanoSuit formed with the optimum concentration of Tween 20 preserves the integrity of an organism’s surface faithfully without interfering with EM imaging. In addition to those results, we found that living organisms possess their own electrical conductors and/or rely on certain properties of the surface to inhibit charging. The NanoSuit seems to prolong the charge-free condition and increase survival time under vacuum. These findings should encourage the development of more sophisticated observation methods

for studying living organisms in an EM. We have now further improved the "NanoSuit" technique to permit observation of wet tissue samples as well as cultured cells by EM. We protect the specimens with a Surface Shield Enhancer (SSE) solution and find that the fine structure of the SSE treated specimens is superior to that of conventionally prepared specimens. The SSE based NanoSuit affords a much higher barrier to gas and/or liquid loss, since it allows more detailed images, it could significantly help to understand the 'real' organization of cells and their sub-cellular substances.

10162-17, Session 4

Three-dimensional imaging of human tissues using recently developed methodology in high-resolution x-ray tomography

Anna Khimchenko, Marzia Buscema, Georg Schulz, Christos Bikis, Simone E. Hieber, Bert Mu?ller, Univ. Basel (Switzerland)

Our body is hierarchically organized down to individual cells. The cutting-edge clinical imaging facilities reach a spatial resolution of a fraction of a millimeter - the biological cells, thus, are invisible. A decade ago, post-mortem X-ray imaging by means of synchrotron radiation enabled the identification of Os-stained ganglion and non-stained Purkinje cells [1,2]. Very recently, even sub-cellular structures, which comprise the nucleolus and the dendritic tree of the Purkinje cells, were extracted by means of phase contrast synchrotron radiation-based hard X-ray tomography [3]. Also recently, conventional, absorption contrast, laboratory-based micro-tomography has been successfully applied to visualize brain components including individual Purkinje cells [4]. For the three-dimensional visualization of brain [2] or the simultaneous visualization of soft and hard tissues [5] the phase contrast mode provides better data quality than the conventional absorption contrast mode [6]. To extend the capabilities of advanced micro computed tomography (?CT) system nanotom® m (GE, Wunstorf, Germany), we have incorporated a double-grating interferometer [7]. This extension enables us to measure not only the attenuation of the X-ray but also the related spatial distribution of the electron density and the scattering of the hard X-rays at the tissue components. In this communication, the increased contrast for the formalin-fixed, calcified human coronary artery and for a part of a human knee with bone and cartilage is illustrated. We are negotiating how far the quality gain of the laboratory-based phase contrast can be driven with respect to the conventional absorption measurements.

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10162-18, Session 4

Three-dimensional microstructure of selected animals *(Invited Paper)*

Felix Beckmann, Helmholtz-Zentrum Geesthacht (Germany)

The Helmholtz Zentrum Geesthacht is operating the user experiments for micro tomography using synchrotron radiation at the beamlines P05 and P07 of the storage ring PETRA III at DESY, Hamburg, Germany. The brilliant X-ray source allows for artefact free tomographic investigations providing a high spatial and high density resolution. In this talk the advantage of this technique will be demonstrated on selected series of small animals. Focus will be given to the concept to access the three-dimensional microstructure of low absorbing and absorbing structures. Furthermore, the application of new phase-contrast techniques will be shown.

10162-19, Session 5

Modeling of the burrowing mechanism by razor clam with a 3D DEM model: role of expanding frequency

Junliang Tao, Sichuan Huang, The Univ. of Akron (United States)

The Atlantic razor clam possesses an exceptional penetration performance via periodical expanding/contracting its body during burrowing. This paper provides insights into the dynamic burrowing process in cohesionless granules from Discrete Element Method (DEM) modeling. A 3D model is developed to capture the key feature of the burrower's kinematics and the dynamic interaction between the cyclically expandable cylindrical body and the surrounding soil. Different expanding frequencies are considered to preliminarily study the effect of the cyclic shape changing over the penetration resistance. Results show that the cyclic expansion/contraction has significant effects on penetration resistance. A critical frequency is identified under which the penetration efficiency is optimal.

10162-20, Session 5

Comparison of live stimuli and 3D printed replicas: preference tests for zebrafish

Tommaso Ruberto, NYU Tandon School of Engineering (United States); Giovanni Polverino, Leibniz-Institut für Gewässerökologie und Binnenfischerei (Germany); Maurizio Porfiri, NYU Tandon School of Engineering (United States)

In recent years, robots have emerged as relevant means for studying individual and social behavior, providing highly customizable and controllable instruments for a wide number of behavioral investigations. As zebrafish is gaining momentum among laboratory animals, several robotics-based paradigms have been proposed to study its complex behavior. However, previous studies have failed to report attraction toward robotic stimuli, comparable with live conspecifics, thereby hindering the capability of robotics-based paradigms to aid the analysis of zebrafish sociality. Here, we investigate this aspect in a within-subject experiment by testing zebrafish and comparing the attraction toward a live conspecific and a 3D-printed replica in binary-choice preference tests. The replica is fabricated to mimic zebrafish morphology and coloration, and it is actuated by a novel four-degree-of-freedom robotic platform along realistic 3D trajectories. Our results show that zebrafish response toward the replica and the conspecific are equivalent, thus confirming the analogous appraisal of the target stimuli. Specifically, the time spent in the vicinity of the stimulus and the average distance from it did not vary as the live stimulus was replaced by the 3D-printed replica. Fish acceleration also did not vary with the stimulus, suggesting that the replica did not evoke stress-related behavior, albeit a fish modestly increased their speed in the presence of the replica.

10162-21, Session 5

Investigation of propulsive characteristics due to traveling waves in continuous finite media

V.V.N. Sriram Malladi, Patrick Musgrave, Pablo A. Tarazaga, Virginia Polytechnic Institute and State Univ. (United States)

The undulating swimming patterns of aquatic animals that develop propulsive forces are of interest in the present work. Lighthill, in the 1960's, has shown that compared to traveling waves, standing waves are highly inefficient for generating propulsive thrust. This study has been the basis of numerous bio-robots that replicate wave-like patterns to swim. Some of these studies use smart materials to actuate and mimic the fin and the tail characteristics of fish. In most of these studies, the undulatory motion of these robots is achieved by discretizing the robot's fin into multiple segments and syncing the oscillatory motion of individual parts to replicate waves. However, these attempts do not use the structural properties of the continuous media to generate waves and add complexity with jointed components.

The present work generates steady state traveling waves in fin-like continuous structures with the help of Macro-Fiber Composites (MFCs). To produce traveling waves, two MFCs simultaneously excite a fin at a common frequency with a preset phase difference. Previous research has shown that optimal traveling waves are developed in structures when the common frequency lies halfway between two adjacent resonant frequencies and the phase difference between the two inputs is 90°. These traveling waves closely replicate the undulatory patterns of aquatic animals. The propulsive forces developed through these waves are experimentally studied and compared with other approaches. The development of traveling waves in fin-like structures and the investigation of propulsive capabilities of such waves is the focus of this paper.

10162-22, Session 5

Zebrafish response to live predator and biologically-inspired robot

Gabrielle Cord-Cruz, Tommaso Ruberto, Daniele Neri, Changsu Kim, Maurizio Porfiri, NYU Tandon School of Engineering (United States)

Biologically-inspired robots are emerging as promising research tools in laboratory experiments to study animal behavior. Specifically, results can be utilized to replace live conspecifics or heterospecifics in behavioral assays. Among animal models, zebrafish are rapidly attaining an important role for their genetic and neural homologies with humans, high stocking density, short inter-generation time, and elevated reproduction rate. Thus, a number of experimental paradigms has been proposed to investigate emotional domains, such as fear and anxiety. However, these approaches are generally based on live stimulus which may result in inconsistent behavioral responses. Building on previous studies, we seek to demonstrate the possibility of utilizing robotic stimuli to elicit fear response in the zebrafish. Specifically, we compare the response of zebrafish to a biologically-inspired 3D-printed replica of an allopatric predator, Astronotus ocellatus, with the response to its live counterpart. We design and develop a novel dedicated platform to actuate the robotic predator along programmable locomotory patterns, affording also body oscillation. We perform experiments on zebrafish and analyze the gathered data through the use of an in-house developed automatic tracking software to measure fish behavior. We utilize the information-theoretic notion of transfer entropy to study the interaction between the predatorial stimuli and focal fish, and shed light on the appraisal of the fear-evoking stimuli by focal subjects. This dataset is expected to provide a compelling basis for further experiments quantifying information flow in fish shoals under a predator threat, as well as clarifying the role of robotics in animal experiments.

10162-30, Session 5

Biomimetic liquid repellent surfaces based on self-organized honeycomb-patterned polymer films

Hiroshi Yabu, Tohoku Univ. (Japan); Jun Kamei, Royal College of Art (United Kingdom)

Pitcher plants have liquid-infused structured surfaces to slip and digest insects, which have oily surfaces on their body, inside of their pods. By mimicking the slipping mechanism of pitcher plant pods, the omniphobic slippery surface has been created by infusing liquid lubricants into porous materials.

We have reported honeycomb-patterned porous films can be prepared by casting polymer solution under humid conditions. By using condensed water droplets onto the surface of cast solutions of polymers as templates, uniformly sized pores were formed on the polymer films after evaporation of solvent and template water droplets. By peeling the top layer of honeycomb films with adhesive tape, the pincushion-like surface structure can be created. This pincushion surface has high water repellency due to their high surface porosity and hydrophobic nature. By infusing lubricants into the pincushion film, omniphobic slippery surfaces can be prepared. When fluorinated lubricants infuse into fluorinated pincushion film, they slip both oil and water droplets with inclined the film only a few angle. Furthermore, the motion of sliding liquids can be controlled by stretching of the film or surface patterning.

In the presentation, we will show the biomimetic liquid repellent surfaces based on self-organized honeycomb films. Moreover, other applications of honeycomb films for stretchable electrodes for epidermal sensing and on-demand separation systems.

10162-24, Session 6

Bio-inspired surfaces with nano-scale structural randomness: from analysis to fabrication and applications *(Invited Paper)*

Hendrik Hölscher, Karlsruher Institut für Technologie (Germany)

As its name suggests the glasswing butterfly (Greta oto) features transparent wings with remarkable low reflectance even for large view angles [1]. This omnidirectional anti-reflection behavior is caused by small nanopillars covering the transparent region of its wings. In difference to other anti-reflection coatings found in nature (moth eye, hawk moth wing, cicada wing) these pillars are not periodically arranged and feature a random height and width distribution. We analyze the specular and diffuse reflection of the surface and explain the concept of transparency by randomness. Such anti-reflective surfaces can be adapted to improve the light collection in solar cells or for efficient anti-reflection displays.

The hierarchical structures found in the scales of the black butterfly (Pachliopta aristolochia), consisting of disordered nano-holes assemblies surrounded by micrometer-spaced triangular ridges, are crucial for controlling light absorption and therefore the butterflies colors and thermoregulation properties. We studied numerically the light harvesting performance of these hierarchical structures. Based on these observations, efficient nano-patterned thin absorbers can be designed for photovoltaics applications. We show that using a lateral phase separation process enables to fabricate disordered nano-holes assemblies with tunable density and size distribution in a resist layer and onto large surfaces.

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10162-25, Session 6

Blue tarantulas and dancing rainbow spiders inspire new color technologies

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Many spiders exhibit vivid colors that are not produced by pigments, but rather by optical interference, diffraction, and scattering — structural colors. Traditionally, structural color research in nature focused on birds, butterflies and beetles. But the long evolutionary history and extreme diversity of spiders provide fruitful new territory. The repeated evolution of blue in large, nearly blind tarantulas and the diversification of sexual display colors in tiny peacock spiders provide two striking examples. Here, we show how tarantula blue is produced using specialized hairs with complex hierarchical structure that greatly reduces iridescence — which has been a key obstacle to the production of synthetic structural colorants without the shimmering effects. On the other hand, the strikingly iridescent scales of the rainbow peacock spider (Maratus robinsoni) can produce every color of the rainbow, and may hold the secrets for future optical device miniaturization. We used an interdisciplinary biomimetic approach to investigate both questions by including techniques such as: morphological characterization (SEM/TEM), phylogenetic analysis, spectrophotometry, optical simulation, and rapid prototyping by 3D nano-printing. Particularly with the rapid prototyping capability, we can create engineering models to test biological hypotheses in a controlled manner that may not be feasible with the living systems. Hence, biomimicry is not only taking what we learned from natural systems to practical human applications, but it is also providing insightful feedbacks and ideas to deepen our understanding of the biological system subject matter during the process.

10162-26, Session 6

Design of bioinspired chirped reflectors using a genetic algorithm

Francesco Chiadini, Univ. degli Studi di Salerno (Italy); Vincenzo Fiumara, Univ. degli Studi della Basilicata (Italy); Antonio Scaglione, Univ. degli Studi di Salerno (Italy)

Broadband reflectors can be achieved as dielectric multilayers in which two dissimilar materials (with high and low refractive index) alternate each other with a certain sequence of their thicknesses. Such structures have been identified in nature in the skin and in the shell of a variety of organisms. In particular, three types of multilayers can be identified: quarter-wave, chirped, and chaotic stacks [1,2]. This work is focused on chirped reflectors possessed by the shells of some gold beetles (e.g. Anopognathus parvulus and Aspidomorpha tecta) giving rise to broadband reflection in the visible wavelength range. The broadband reflectivity is achieved by progressively decrease the thickness of the layer thickness from the outermost to the innermost layer.

Chirped stacks with layer thicknesses decreasing according to an arithmetic or geometric progression, have been studied in the past [3]. However, an insight of the cuticle section of the Aspidomorpha tecta beetle shows a chirped structure with an irregular decreasing of the layer thicknesses [1].

Therefore, we numerically analyzed irregular chirped structures using a genetic algorithm to design a multilayer with the same broad reflection band. Given a desired level of reflectance, the genetic algorithm generates the sequence of the stacks' layers to obtain the desired spectrum with a very large reflection band. Results show that the irregular chirped multilayer with layer thicknesses obtained using the genetic algorithm outperforms the regular chirped structure in designing the desired broad reflection band.

[1] A. R. Parker and D. R. Mckenzie and M. C. J. Large, "Multilayer reflectors in animals using green and gold beetles as contrasting examples," J. Exper. Biol. 201, 1307–1313 (1998)

[2] J. A. Bossard and L. Lin and D. H. Werner, "Evolving random fractal Cantor superlattices for the infrared using a genetic algorithm," J. R. Soc. Interface 13, 20150975 (2016)

[3] O. S. Heavens and Heather M. Liddell, "Staggered Broad-Band Reflecting Multilayers," Appl. Opt. 5(3), 373-376 (1966)

10162-27, Session 6

Substrate-free morpho-color materials fabricated by a simple mass-production process based on new principles

Akira Saito, Osaka Univ. (Japan) and RIKEN (Japan) and SPring-8 (Japan); Jumpei Ohga, Yuji Kuwahara, Osaka Univ. (Japan)

Morpho butterfly's blue is known as a typical structural color. On the other hand, it has a physically mysterious feature. The blue has high reflectance produced by interference from an ORDERED nanostructure on their scale, whereas the color has scarcely angular dependence, which contradicts the interference. This mystery is attributed to a specific nanostructure having nano-DISORDER to prevent the rainbow hue. After successful prove of this principle by emulating the 3D nanostructures, wide potential applications of this specific?color have been found due to its characteristics such as fade-free, pigment-free, save materials, and high reflectance of a single color in wide angles, etc. However, true applications require many developments such as mass-production, control of optical properties, optical simulation on the nano-disorder, etc., which have recently been overcome step by step. The remaining key issue is the "substrate-free" condition, for wide applications on the free-shape. Actually, all our processes based on the nanoimprint for mass-production have been accompanied with a thick substrate designed with a specific nano-disorder, which has limited fatally the variety of applications. Following the successful and quite simple fabrication of the substrate-free Morpho-Powders (2014) and thin film(2015), we found new principles to fabricate easily and stably the nano-patterned flexible thin film by maintaining the specific properties. Our principles will extend the applications of the specific color, giving the free-shape of coloration. Not only for the Morpho-materials, our finding will serve to mass-produce the functional thin film in more general purpose.

10162-28, Session 6

Bioinspired multicontrollable metasurfaces and metamaterials

Akhlesh Lakhtakia, Douglas E. Wolfe, Mark W. Horn, The Pennsylvania State Univ. (United States); John Mazurowski, The Pennsylvania State Univ. Electro-Optics Ctr. (United States); Arnold Burger, Fisk Univ. (United States); Partha P. Banerjee, Univ. of Dayton (United States)

Not only does multifunctionality abound in the biological word, but so also does multicontrollability. Thus, often the same sound can be uttered using two or three different configurations of the tongue and the buccal cavity, and multiple modes of locomotion can be used by an organism to propel itself from one location to another. Inspired by biological multicontrollability, we have devised the concept of multicontrollable metasurfaces. Comprising electrically small elements made of diverse pixels each of which is either magnetically controlled, or thermally controlled, or electrically controlled, or photonically controlled, a metasurface could be either homogeneous or graded on the wavelength scale. Stacks of parallel multicontrollable metasurfaces would function as multicontrollable metamaterials.

10162-29, Session 6

Capillary-based grip in biological and engineered systems: a comparative review on scalability and geometry

Peter van Assenbergh, Jay van den Berg, Paul Breedveld, Dimitra Dodou, Technische Univ. Delft (Netherlands)

Capillary-based grip in biological and engineered systems: a comparative review on scalability and geometry

Grip on wet substrates is essential for the survival success of some biological organisms, since water in natural environments is ubiquitous. Some organisms even exploit the presence of water to generate high adhesive or frictional forces by means of capillary bridge formation between their body and the substrate. For example, tree-frog toe-pads are covered with hexagonally packed pillars, separated by deep grooves, which allow forming multiple separated menisci of water, mixed with mucus secreted by the toe pad [1], [2]. Dock beetles (Gastrophysa viridula) bear adhesive setae on their feet, which form capillary bridges strong enough to support the animal [3].

Also in industry, capillary adhesion is used as a mechanism for gripping or sticking, for example to manipulate micro-scale objects [4], [5].

In this review, we compare capillary-based adhesion and friction in biological and engineered systems, with geometry and scalability as moderators. We found that biological gripping systems consist of hierarchical structures, leading to a large number of capillary bridges and strong adhesion. Capillary-based engineered systems, on the other hand, generally rely on a limited number of capillary bridges and thus are mostly suitable for gripping micro-scale objects only. Industry would benefit from biologically-inspired scaled up capillary-based grippers, allowing gripping of larger objects. Next to the overview of biological and engineered capillary-based grippers, our review provides a theoretical framework of capillary adhesion, which can be used to deduced in what ways engineers can learn from the biological examples when it comes to geometry and scalability of engineered capillary-based grippers.

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10162-32, Session PMon

Robotic controller

Subrat Mahapatra, Kevin Nickels, Hoa Nguyen, Trinity Univ. (United States)

This paper combines several algorithms to improve the performance robots determining the source of a chemical spill. We use a state machine that switches into different behavior modes depending on the sensory data of the environment. The robot starts out in a traditional patrol mode where it wanders from waypoint to waypoint on patrol. After discovery of the plume, the controller then shifts to a plume tracking state using a combined algorithm inspired by E. Coli bacteria and the silkworm moth. The E. Coli bacteria uses a biased random walk in order to move towards the source. Otherwise, they perform random walk in a non-gradient environment. The moth algorithm has the advantage of taking into account factors such as wind direction and plume concentration at the location of the reading. Combining the chemotactic strategies of E. Coli and moth allows the robot to detect the odor source in a more realistic dynamic plume setting where the wind direction might not be detected. In this system if the robot loses the plume, the robotic controller then switches states into a plume recovery mode which is based on the E. coli algorithm. The controller has been simulated as well as tested on a small-scale robot that imitates these biological organisms in order to locate the source of the chemical plume. Further work could test out other biologically inspired algorithms using this state machine to determine the rates of success between multiple algorithms.

10162-33, Session PMon

Probing of micro and nano-rheological behavior of insect hemolymph using magnetic actuation

Pavel Aprelev, Peter H. Adler, Konstantin G. Kornev, Clemson Univ. (United States)

Hemolymph in insects plays a vital role in processes that range in scale from macroscopic – such as primary wound healing – to microscopic – such as flowing through vessels to deliver nutrients – to nanoscopic – such as fending off bacteria and viruses. From a rheological perspective, hemolymph is a suspension of adherent and non-adherent micron-sized hemocytes suspended in plasma. Even though at the macro-scale the suspension may behave as a single-phase liquid, it has been a long-standing challenge to measure its rheological properties at the micro- and nano-scales, where the effects of hemocytes can be significant. We discuss the analysis of the viscosity of butterfly hemolymph when the droplet size is measured in nanoliters, a size which cannot be addressed by the best available rheological methods dealing with microliter droplets. We probe the nano-rheology of hemolymph by suspending magnetic nano-rods in a droplet of hemolymph. Magnetic rotational spectroscopy was employed by rotating the probe with a rotating magnetic field of various frequencies. These experiments were conducted in a nitrogen atmosphere preventing the effects of clotting induced by oxygen. Studies of hemolymph of adult butterflies and larvae show significant differences in its rheological behavior.

10162-34, Session PMon

Dropwise condensation using bioinspired surfaces

Blake Naccarato, Taeseon Hwang, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Plants, amphibians, and insects alike utilize hydrophobicity to improve their chances of survival. The leaves of the lotus flower are self-cleaning by virtue of their hydrophobicity. The pygmy gecko's hydrophobic skin and footpads allow it to stand on water. The Namib desert beetle collects fog on its hydrophobic wings. The latter example is similar to the application of hydrophobic surfaces to condensation heat transfer enhancement.

A hydrophobic surface promotes dropwise condensation. While the Namib desert beetle relies on dropwise condensation to capture more water in an arid environment, a condensation heat exchanger uses it to collect more condensate, improving heat transfer. Condensation heat transfer is usually carried out on metal surfaces, which tend to be hydrophilic. Filmwise condensation dominates on such surfaces. Hydrophobic surface treatments can cause a change from filmwise to dropwise condensation over a range of subcooling temperatures. Condensate more readily departs the surface as droplets than as a film, enhancing heat transfer.

A tube condensation heat exchanger (TC-HEX) and plate condensation heat exchanger (PC-HEX) have been developed in order to characterize and visualize condensation on hydrophobic surfaces. The TC-HEX features resistance temperature detectors at coolant inlet and outlet, as well as thermocouples and pressure transducers to monitor ambient conditions. This allows for determination of the heat transfer coefficient. The PC-HEX features a large viewport. A high-speed camera is used to observe condensation on a flat plate sample. Image analysis of the high-speed footage allows for direct measurement of parameters relevant to existing population models of dropwise condensation.

10162-36, Session PMon

Sensitive photoreceiver based on carbon nanotube / tobacco cell composite material

Heinz C. Neitzert, Università degli Studi di Salerno (Italy); Giovanni Landi, Univ. degli Studi di Salerno (Italy)

A new type of composite material has been realized by mixing tobacco cells with multi-walled carbon nanotubes. The new composite material, had initially, as previously reported [1], very interesting mechanical as well as electrical properties. In this initial stage a rather high conductivity has been measured, when contacting the device through coplanar evaporated gold contacts. However, after prolonged application of a high electric field, the conductivity strongly decreased for some orders of magnitude.

More than two years of room temperature storage of the bio/nano-composite sample did not alter the mechanical properties of the sample. A detailed optical investigation, revealed the semitransparency of the composite film in the visible spectral range. The dark conductivity of the sample was still very low as before the storage period with currents in nA-range. Illuminating the sample with a low intensity white LED light we observed a strong and stable resistivity modulation, that permitted to use the bio-composite as a sensitive photoreceiver with linear characteristic.

Herewith we want to show opportunities and limitations of this new type of this bio-nano composite photosensor and discuss the possible mechanisms, responsible for the strong photoconduction.

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Conference 10163: Electroactive Polymer Actuators and Devices (EAPAD) XIX

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10163-500, Session Plen

EAP artificial muscle actuators for bio-inspired intelligent social robotics

David F. Hanson, Hanson Robotics, Ltd. (United States)

Bio-inspired intelligent robots are coming of age in both research and industry, propelling market growth for robots and A.I. However, conventional motors limit bio-inspired robotics. EAP actuators and sensors could improve the simplicity, compliance, physical scaling, and offer bio-inspired advantages in robotic locomotion, grasping and manipulation, and social expressions. For EAP actuators to realize their transformative potential, further innovations are needed: the actuators must be robust, fast, powerful, manufacturable, and affordable. This presentation surveys progress, opportunities, and challenges in the author's latest work in social robots and EAP actuators, and proposes a roadmap for EAP actuators in bio-inspired intelligent robotics.

10163-1, Session 1

Electroactive polymers for healthcare and biomedical applications *(Keynote Presentation)*

Siegfried G. Bauer, Johannes Kepler Univ. Linz (Austria)

Electroactivity was noticed early in biological substances, including proteins, polynucleotides and enzymes, even piezo- and pyroelectricity was found in wool, hair, wood, bone and tendon. I will start the presentation with hydroxyapatite – a material full of surprises. Hydroxyapatite forms about 60 to 70 % of the mass of human and animal bone. In early investigations of piezo- and pyroelectricity in bone it was believed that the observed effects stem from the polar collagen component of bone, since hydroxyapatite was believed to be isostructural with the centrosymmetric apatite. Surprisingly later on a noncentrosymmetric structure was found, together with quite strong piezo- and pyroelectricity in this natural material. Although there is still a strong debate about the physiological importance of electroactive effects in biological materials, this example shows how widespread electroactive phenomena are in natural materials. Let's draw inspiration from nature and widen the utilization of electroactive polymers towards (mobile) healthcare and biomedical applications. Ferroelectrets, internally charged polymer foams with a strong piezoelectric thickness coefficient are already employed in biomedical sensing, for example as blood pressure and pulse sensor, as vital signs monitor or for the detection of tonic-clonic seizures. Piezo- and pyroelectric polymers are booming in printed electronics research, providing electronic skin the ability to "feel" pressure and temperature changes, or to generate electrical energy from vibrations and motions, even from contractile and relaxation motions of the heart and lung. Dielectric elastomers on the other hand are pioneered by stretchsense as wearable motion capture sensors, monitoring pressure, stretch, bend and shear, quantifying comfort in sports and healthcare. On the cellular level, electroactive polymer arrays are used to study mechanotransduction of individual cells. Most recent efforts are devoted to implantable electroactive biomedical devices. Already with the currently available science and technology, we are at the verge of witnessing the demonstration of truly complex bionic systems. Without much doubt, the future of electroactive polymer materials is bright.

10163-2, Session 1

From research to production *(Invited Paper)*

Gabor M. Kovacs, EMPA (Switzerland)

In the past decades the development of compliant dielectric materials, capable of storing high electric energy density, is the object of considerable research e?orts for commercial applications. Compared to the widely used soft dielectrics as compliant insulators, only a small variety of commercially products based on dielectric polymer transducers are available on the market up to date. A whole bunch of research activities worldwide has created a lot of very useful knowledge; but many researchers have been faced to different obstacles to manufacture devices for demonstrations. However, building handy demonstrators is one of the most relevant action in order to attract the interest of decision makers of industrial companies. Moreover, low cost devices strictly require highly efficient production methods and facilities to become competitive on the market. This aspect contains the ultimate requirement especially for very high output rates and represents one of the major topic at most negotiations. All technological problems linked to this issue have been addressed only a little in the past R+D activities and are still widely not satisfactory solved. The present talk will provide an overview of the options for opening the door of industrial production of polymer transducers and the remaining obstacles to be solved for the next step. In particular, the most relevant actions to be taken for enabling high capacity production at very low cost will be discussed, which have an essential impact on the direction of future research activities.

10163-3, Session 2

Proximity and touch sensing using deformable ionic conductors *(Invited Paper)*

John D. W. Madden, Yuta Dobashi, Mirza S. Sarwar, Eden C. Preston, Justin K. M. Wyss, The Univ. of British Columbia (Canada); Vincent Woehling, Tran-Minh-Giao Nguyen, Cédric Plesse, Frédéric Vidal, Univ. de Cergy-Pontoise (France); Sina Naficy, Geoffrey M. Spinks, Univ. of Wollongong (Australia)

There is increasing interest in creating bendable and stretchable electronic interfaces that can be worn or applied to virtually any surface. The electroactive polymer community is well placed to add value by incorporating sensors and actuators. Recent work has demonstrated transparent dielectric elastomer actuation as well as pressure, stretch or touch sensing. Here we present two alternative forms of sensing. The first uses ionically conductive and stretchable gels as electrodes in capacitive sensors that detect finger proximity. In this case the finger acts as a third electrode, reducing capacitance between the two gel electrodes as it approaches, which can be detected even during bending and stretching. Very light finger touch is readily detected even during deformation of the substrate. Lateral resolution is achieved by creating a sensor array. In the second approach, electrodes placed beneath a salt containing gel are able to detect ion currents generated by the deformation of the gel. In this approach, applied pressure results in ion currents that create a potential difference around the point of contact, leading to a voltage and current in the electrodes without any need for input electrical energy. The mechanism may be related to effects seen in ionomeric polymer metal composites (IPMCs), but with the response in plane rather than through the thickness of the film. Ultimately, these ionically conductive materials that can also be transparent and actuate, have the potential to be used in wearable devices.

10163-4, Session 2

Distributed sensing: multiple dielectric elastomer sensors on a single channel

Andreas Tairych, The Univ. of Auckland (New Zealand); Iain A. Anderson, The Univ. of Auckland (New Zealand) and StretchSense (New Zealand)

"Soft, stretchable, and unobtrusive". These are some of the attributes frequently associated with dielectric elastomer (DE) sensors in literature. Because of these characteristics, users are very likely to tolerate the presence of wearable sensors in their clothes, or on their skin. However, while DE sensors themselves are soft, they still require rigid circuit boards, with a separate sensing channel, and a set of wires each. Detailed body motion capture requires the integration of a substantial number of sensors into garments. This can lead to a considerable amount of additional equipment, with the possibility of obstructing movement, or even altering user behaviour.

We address this issue by daisy-chaining conductive fabric sensors, and connecting them to a single sensing channel, with only one set of wires. The sensors are strain dependent capacitors, made from conductive fabric electrodes and silicone dielectrics. External resistors are used to connect individual sensors, thus forming a transmission line. A sensing algorithm applies different sensing frequencies, and calculates the strain dependent capacitances of each sensor. A mathematical model is used to size the external resistors accordingly, and to predict the response of the transmission line to sensor deformation. Experiments are carried out to validate and assess the performance of this sensing model.

Previous work has demonstrated how a transmission line model can be applied to detect multiple deformations on a single DE sensor. In contrast, our approach is targeted towards efficient and unobtrusive measurement of sensors distributed all across the body.

10163-5, Session 2

Monitoring diver health with dielectric elastomer sensors

Christopher R. Walker, Iain A. Anderson, The Univ. of Auckland (New Zealand)

Diving is crucial to the oil and gas industry, search and rescue, and is even done recreationally by millions of people. There is a growing need however, to monitor the health and activity of divers. One example of this is when a diver ascends; the ambient pressure decreases, causing the compressed air in the lungs to expand. If a diver ascends too quickly, without exhaling, the lungs can over-expand causing pulmonary barotrauma. Monitoring and providing feedback on diver respiration could help prevent this form occurring. To further explore diver health monitoring we have coupled dielectric elastomer (DE) sensors to a wetsuit worn by the pilot of a human-powered wet submarine. The pilot lies face down, completely encapsulated in a hull, while pedalling to propel the submarine forward. The aim of this study was to demonstrate our ability to monitor the respiration and exertion of the pilot.

This study was in collaboration with the University of Auckland's human-powered submarine team, Team Taniwha. Three waterproof DE sensors were fabricated and coupled to the pilot. The first two sensors were attached to the knee joints, measuring the activity of the pilot. The third sensor was attached to the pilot's chest to monitor respiratory rate. The submarine was pedalled in a dive pool from one corner to the opposite. Data from the sensors was logged for post analysis.

This paper applies DE sensor technology to monitor the health and activity of a diver. The experimental set-up and results are presented.

10163-6, Session 2

Dual sensing-actuation artificial muscle based on polypyrrole-carbon nanotube composite

Johanna Schumacher, Arquimea Ingeniería, S.L.U. (Spain); Victor H. Pascual, Toribio Fernández Otero, Univ. Politécnica de Cartagena (Spain)

Dual sensing artificial muscles based on conducting polymers driven by electrochemical reactions can allow the development of artificial proprioceptive devices. Several sensors and a faradaic motor work simultaneously in one uniform device driven by reaction of the constitutive material, like natural muscles do. Motor and sensors can be controlled at any working time via the same two connecting wires. Here, the applicability of a composite of polypyrrole and carbon nanotubes for dual sensing bilayer artificial muscles was investigated. The artificial muscle performs large bending motions up to 127 degrees under faradaic control and shows simultaneously sensing abilities of the electrochemical working conditions. Both, the consumed energy and the potential hysteresis sense the available electrochemical conditions, here in particular the scan rate. The polypyrrole-carbon nanotube bilayer is a dual sensing-motor. From the electrochemical responses the actuation and energetic sensing equations are determined for further development of a control system.

10163-7, Session 2

Operation tools with dielectric elastomer pressure sensors

Holger Böse, Johannes Ehrlich, Fraunhofer-Institut für Silicatforschung ISC (Germany)

A new class of dielectric elastomer sensors with high sensitivity for compression load was developed recently. The basic design of the sensors exhibits two profiled surfaces between which an elastomer film with an electrode layer is located. All components of the sensor are prepared with silicone by dye molding and blade casting processes. Depending on details of the sensor design, various effects can contribute to the enhancement of the capacitance. The intermediate elastomer film is stretched upon compression and electrode layers on the elastomer profiles and in the intermediate elastomer film approach each other. Different designs of the compression sensor give rise to very different sensor characteristics in terms of the dependence of electric capacitance on compression force.

Beside the detection of pressure in various environments, such dielectric elastomer sensors can also be used for operation tools in man-machine interfaces. This potential is demonstrated with some examples. In a first application, a touch pad with six pressure-sensitive fields is presented. The corresponding sensors in the touch fields detect the exerted forces of the finger and display them in terms of the measured capacitances on a screen. Moreover, the brightness of LEDs is controlled by the strength of the finger force. As a second example, the integration of sensor-based control fields on an automotive steering wheel is shown. Here, the sensor signals are capable to control sound, brightness, heating and ventilation. Finally, the sensors can also be used in fabrics to control arbitrary functions of wearable electronic devices. The examples demonstrate the high performance of the dielectric elastomer pressure sensor technology for novel operation tools.

10163-8, Session 3

Bottom-up approaches to multi-functional materials and artificial morphogenesis *(Invited Paper)*

Stoyan Smoukov, Univ. of Cambridge (United Kingdom)

Active materials, such as artificial muscles, have experienced intense growth, including muscles actuated by electric fields (low and high voltages), pH gradients, temperature, and even light. Most of the time, however, research is split up between the different mechanisms of actuation with little overlap between them. In addition, current processes for making artificial muscles require manually defining special features and layering of multiple materials. In the best cases these processes are automated and made precise by lithography, which exemplifies the best of top-down precision fabrication. The downside of such methods is their low throughput, however, and expensive infrastructure. Bottom up methods can be very energy and material-efficient, but often lack the precision and complexity that could be achieved in top-down methods. We combine naturally occurring structuring on the micro- and nano-level to design hybrid syntheses, with bottom-up approaches and their typically high efficiencies and scalability, yet with patterning resolution approaching and sometimes even exceeding that achievable by top-down lithographic methods. This is done by various confinements of the chemical reactions.

We show examples of engineering the symmetry breaking and dynamics for multiple structures and processes, on multiple lengthscales – from nanometers to centimeters. We demonstrate the formation of Janus and other asymmetric particles, which form as a result of coupling of chemical reactions to non-linear mechanical properties of materials[1,2]. We also demonstrate the opposite effects – how mechanical deformations and molecular interactions can help one simplify chemical syntheses[3]. Finally, we describe how we synthesize conductive polymers in the 1 nm confinement of the pores of metal-organic frameworks (MOFs).[4] Thus we achieve one of the first conductive MOF-polymer hybrids. We also for the first time remove the MOF from such a composite to reveal a nanostructured conductive polymer (nano-PEDOT) with macroscopic dimensions and nanoscale structure and ordering. We characterize these with a battery of techniques to show the nature of the synthesized polymer. We believe such extreme templating methods hold high promise for supercapacitors, electrochemical catalysis, and sensitive chemical detectors.

One particular consequence of confining chemical reactions to different spatial domains is the promise of easier design of multifunctional materials. Instead of designing all the desired functions in a single molecule, we use controlled internal phase separation in a material to introduce existing materials with already optimized functions, and interweave them into one.[5] With this combinatorial approach we show how spatial separation of just 3 phases and 20 functions would lead to over 8000 trifunctional materials. We demonstrate such interpenetrating networks with the separate and synergistic emerging functions. One of the most exciting developments is recent materials capable of both sensing and actuation. Such proprioceptive combinations could lead to autonomous material robotics.[6]

Finally, we show the recently discovered process of artificial morphogenesis through which by controlling phase transitions in emulsion droplets, we can achieve a rich variety of regular geometric shapes.[7] In addition to the technological advantages of such sustainable, scalable processes, they raise also fundamental questions in materials science, chemistry and physics. Artificial materials exhibiting symmetry breaking, such as dynamic shape-change behaviour, are parsimonious, compared to biological systems, both in terms of number of components and mechanisms. This elegance allows us to study in greater fundamental detail their mechanisms and potential to control and adapt such behaviour.

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10163-9, Session 3

Parameters design of the dielectric elastomer spring-roll bending actuator

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Dielectric elastomers are novel soft smart material that could deform sustainably when subjected to external electric field. That makes dielectric elastomers promising materials for actuators. In this paper, a spring-roll actuator that would bend when a high voltage is applied was fabricated based on dielectric elastomer. Using such actuators as active parts, the flexible grippers and inchworm-inspired crawling robots were manufactured, which demonstrated some examples of applications in soft robotics. To guide the parameters design of dielectric elastomer based spring-roll bending actuators, the theoretical model of such actuators was established based on thermodynamic theories. The initial deformation and electrical induced bending angle of actuators were formulated. The failure of actuators was also analyzed considering some typical failure modes like electromechanical instability, electrical breakdown, loss of tension and maximum tolerant stretch. Thus the allowable region of actuators was determined. Then the bending angle-voltage relations and failure voltages of actuators with different parameters, including stretches of the dielectric elastomer film, number of active layers, and dimensions of spring, were investigated. The influences of each parameter on the actuator performances were discussed, providing meaningful guidance to the optical design of the spring-roll bending actuators.

10163-10, Session 3

Integrated sensing and actuation of dielectric elastomer actuator

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A dielectric elastomer (DE) is a type of soft actuating material, the shape of which can be changed under electrical voltage stimuli. DE materials have great potential in applications involving energy harvesters, micromanipulators, and adaptive optics. In this paper, a stripe DE actuator is designed and fabricated, and characterized through several experiments. Considering the actuator's capacitor-like structure and its deform mechanism, detecting the actuator's displacement through the actuator's circuit feature is a potential approach. A self-sensing scheme that adds a high frequency probing signal into actuation signal is developed. A Fast Fourier Transform (FFT) algorithm is used to extract the magnitude change of the probing signal, and a linear fitting method and an artificial neural network approach are utilized to reflect the relationship between

the probing signal and the actuator's displacement. Experimental results demonstrated that the DE strip actuator can perform simultaneous sensing and actuation.

10163-11, Session 4

Properties of polypyrrole polyvinilsulfate films for dual actuator: sensing systems

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In the dense gel that is the intracellular matrix forming part of living cells electrochemical reactions take place provoking the interchange of ions and water with the surroundings. Systems containing conducting polymers mimic this feature of biological organs. In particular, conducting polymers are being studied as dual sensing-actuating reactive materials giving new multifunctional sensing-actuators, which allow the construction and theoretical description of artificial proprioceptive devices. Here films of polypyrrole/dodecyl benzene sulfonate (PPy-DBS) coating a platinum electrode were submitted to potential sweeps at different sweep rates in order to explore if the polymer reaction senses the working electrochemical conditions. The effective consumed electrical energy per cycle follows a fast decrease when the scan rate increases described by the addition of two exponential sensing functions. Moreover, the variation of the hysteresis from the parallel charge/potential loop with the scan rate is also described by the addition of two exponential functions. In both cases the exponential functions fitting results at low scan rates are related to reaction-driven conformational movements of the polymer chains, being closer to biochemical conformational and allosteric sensors. The second exponential functions fitting results at high scan rates are related to diffusion kinetic control, being closer to present electrochemical sensors.

10163-12, Session 4

Dynamic instability of dielectric elastomer actuators driven by a combined AC and DC electric loading

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Dielectric elastomer actuators are promising contenders to be used in biomimetic applications. An operational instability emanating from the interaction of electrostatic and mechanical forces; however, limits their useful range of deformation. While the nature of this electromechanical instability is well-explored in case of quasi-static actuation, its analysis in case of dynamic actuation has been of continued interest. This paper investigates the dynamic instability of dielectric elastomer actuators subjected to an equal biaxial prestress, and a combination of the DC and AC voltage bias.

To this end, a standard sandwich model of a homogeneously deforming hyperelastic DEA is considered in the present analysis. An energy-based approach is used to derive the equation of motion when the actuator is driven by an AC voltage with a non-zero DC bias. The energy dissipation is modeled in terms of an equivalent viscous damping coefficient. The governing equation is integrated numerically to obtain the time-history response of stretches along the three principal directions. The critical value of the electric field, corresponding to the dynamic instability, is identified as the one at which the response of the actuator turns aperiodic. It is further shown that this critical value depends strongly on the frequency of the harmonic excitation, extent of the biaxial prestress, and the DC offset. For various combinations of the DC offset and prestress value, trends of variations of the critical electric field with the frequency of excitation are generated. The inferences reveal that a judicious combination of prestress and DC offset can be preferential in designing the DEAs under specific operational requirements.

10163-13, Session 4

Preliminary results on the fatigue life characterization of a styrenic dielectric elastomer membrane

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Recently, a styrenic rubber membrane (commercialized under the name of "THERABAND YELLOW 11726") demonstrated excellent electromechanical properties for the development of high power density and highly efficient dielectric elastomer transducers (DETs). In particular, in an experimental application as generator, an inflated circular diaphragm DET based on this material made it possible to consistently convert pneumatic energy into electricity at a maximum energy density per cycle and power density greater than 400 J/kg and 650 W/kg, respectively, with even higher numbers being expected for DETs configured so as to have the material working in uniform states of deformation.

As for any other existing dielectric elastomer material, these experimented performances can however be sustained for a limited number of cycles only, after which the DET will fail irreversibly. To date, very little information is available on the fatigue life performances of dielectric elastomer materials and of the transducers made thereof.

Having identified the electrical breakdown as the most probable mode of DET failure, this paper reports for the first time on a set of lifetime constant-electric-stress tests conducted on the considered styrenic dielectric elastomer membrane.

Specifically, the paper starts with a description of the employed experimental set-up and procedures. Then, it summarizes the obtained experimental results. Finally, it concludes with a discussion on how the acquired data could be used in a design procedure to find optimal tradeoffs between DET performance and lifetime/reliability.

10163-14, Session 4

Insights on the mechanism of piezoelectricity in P(VDF-TrFE) copolymer as a function of crystallinity by molecular dynamics simulation

Farzin Rahmani, Sasan Nouranian, Farhad Farzbod, Univ. of Mississippi (United States)

In this work, we performed a series of molecular dynamics simulations on a piezoelectric copolymer, i.e., poly[(vinylidenefluoride-co-trifluoroethylene] (P(VDF-TrFE)), to elucidate the effects of copolymer processing (stretching and annealing) on the percentage of copolymer crystallinity, as well as the α- to β crystal phase ratio, piezoelectric constant, and net dipole moment. To our best knowledge, the processing-piezoelectricity relationship is not well understood for the P(VDF-TrFE) copolymer and the current work fills the current scientific gap by providing molecular insights on the relevant mechanisms. We created the initial copolymer structure in BIOVIA Materials Studio® by packing 50 chains of random P(VDF-TrFE) copolymers (70% VDF and 30% TrFE) with 200 monomer units per chain in a 3D-periodic simulation cell of the size 82x82x82 Å3. We then exported the structure to the open-source LAMMPS software and performed an energy minimization on it, followed by an NPT simulation at 298 K and 1 atm for 10 ns, to equilibrate the structure. We achieved a final density of 1.78 g/cubic cm for the copolymer system. We then deformed six similar structures in the z-direction with a constant strain rate of 100 million/s to the final strains of 100%, 200%, ..., 600%, and performed an annealing of the each stretched system at 408 K using an NPT ensemble for 10 ns. Subsequent to the annealing process, we quenched the systems to 298 K. We later performed an X-Ray Diffraction (XRD) on the systems and analyzed the resulting crystal structures. Moreover, we calculated the net dipole moment for the copolymer and analyzed the relaxation of the system as a function of time. Our preliminary results show that the prevalence of β-phase crystals increases with the annealing process, signifying a better piezoelectric property for the copolymer.

10163-15, Session 4

A mathematical model for an integrated self priming dielectric elastomer generator

Patrin K. Illenberger, Katherine E. Wilson, E.-F. Markus Henke, Udaya K. Madawala, Iain A. Anderson, The Univ. of Auckland (New Zealand)

Dielectric Elastomer Generators (DEG) can capture energy from natural movement sources such as wind, tidal and human locomotion. The harvested energy can be used for low power devices such as wireless sensor nodes and wearable electronics. A challenge for low power DEG is overcoming the losses associated with charge management. A circuit which can do this exists: the Self Priming Circuit (SPC) which consists of diodes and capacitors. The SPC is connected in parallel to the DEG where it transfers charge onto/off the DEG based on changes in the DEGs capacitance. Modeling and experimental validation of the SPC has been performed in the past, allowing design and implementation of effective SPCs which match a particular DEG. While the SPC is effective, it is still an external circuit which adds unnecessary mass and cost to the DEG. By splitting the DEG into separate capacitors and using them to build an SPC, the Integrated SPC (ISPC) can be realized. This reduces the components required to build a SPC/DEG and improves the performance. This paper presents a mathematical model with experimental validation for a first order ISPC.

10163-16, Session 5

Fused filament 3D printing of ionic polymer-metal composites for soft robotics *(Invited Paper)*

Kam K. Leang, James D. Carrico, The Univ. of Utah (United States)

Additive manufacturing techniques are used to create three-dimensional structures with complex shapes and features from plastic and/or metal materials. For example, the fused filament three-dimensional (3D) printing approach utilizes non-electroactive plastics, such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), to build structures and components in a layer-by-layer fashion for a wide variety of applications. Presented here is recent work on a fused filament 3D-printing technique using electroactive ionomeric polymer material to create 3D soft ionic polymer-metal composite (IPMC) structures for applications such as soft robotics, biomedical systems, and bio-inspired actuators and sensors. The 3D printing technique overcomes some of the limitations of existing manufacturing processes for creating IPMCs, which includes limited shapes and sizes and time-consuming steps. The 3D printing process is described in detail, where first a precursor material (non-acid Nafion precursor resin) is extruded into a thermoplastic filament for 3D printing. A custom-designed 3D printer is described which utilizes the filament to manufacture custom-shaped IPMC actuators. The 3D printed samples are hydrolyzed in an aqueous solution of potassium hydroxide and dimethyl sulfoxide, followed by application of platinum electrodes. The performance of 3D-printed IPMC actuators are presented, along with example soft-robotic devices to demonstrate the potential of this process. Technical challenges and future research directions are also highlighted for the 3D printing process involving IPMCs.

10163-17, Session 5

Producing intricate IPMC shapes by means of painting and printing

Sarah Trabia, Zakai Olsen, Taeseon Hwang, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Ionic Polymer-Metal Composites (IPMC) are common soft actuators that are Nafion® based and plated with a conductive metal, such as platinum, gold, or palladium. Nafion® is available in three forms: sheets, pellets, and water dispersion. Nafion® sheets can be cut to the desired dimensions and are best for rectangular IPMCs. However, the user is not able to change the thickness of these sheets by stacking and melting because Nafion® does not melt. A solution to this is Nafion® pellets, which can melt. These can be used for extrusion and injection molding. Though Nafion® pellets can be melted, they are difficult to work with, making the process quite challenging to master. The last form is Nafion® Water Dispersion, which can be used for casting. Casting can produce the desired thickness, but it does not solve the problem of achieving complex contours. The current methods of fabrication do not allow for complex shapes and structures. To solve this problem, two methods are presented: painting and printing. The painting method uses Nafion® Water Dispersion, an airbrush, and vinyl stencils. The stencils can be made into any shape with detailed edges. The printing method uses Nafion® pellets that are extruded into filaments and a commercially available 3D printer. The models are drawn in a Computer-Aided Drawing (CAD) program, such as SolidWorks. The produced Nafion® membranes will be compared with a commercial Nafion® membrane through a variety of tests, including Fourier Transform Infrared Spectroscopy, Scanning Electron Microscope, Thermogravimetric Analysis, Dynamic Mechanical Analysis, and Optical Microscope.

10163-18, Session 5

Study of the electrochemical capabilities of ionic polymer-metal composites using scanning electrochemical microscopy

Craig Anderson, Sarah Trabia, Taeseon Hwang, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Ionic Polymer-Metal Composites (IPMCs) is a smart actuator that is Nafion® based and plated with a conductive material, such as platinum. When a voltage is applied to the surface, the free-moving cations and water molecules move to the negatively charged side, causing it to swell and forcing the IPMC to actuate. IPMCs offer promising solutions for biomimetic applications due to their light weight, low input voltage, and the ability to work safely in water and produce large deformations. However, their electrochemical behavior and performance under long-term cycling is still largely unstudied. Scanning electrochemical microscopy (SECM) was implemented to study the electrochemical behavior of IPMC surfaces under dynamic voltage conditions. Using an ultramicroelectrode (UME) probe, mounted and polished IPMC samples were tested in situ to examine current density as a function of applied voltage over multiple cycles. The samples are submerged in an electrolyte along with a Reference Electrode and Counter Electrode. A low amount of voltage was applied to the IPMC samples to replicate actuation and the resulting electrochemistry reactions were recorded by the UME probe. A variety of samples were tested, including a complete IPMC, IPMC with one side of the platinum coating sanded off (exposing the Nafion® membrane), IPMCs with different surface coatings (Pt, Pt-Pd, and Pd), and different surface coating thicknesses was investigated. The tests conducted include cyclic voltammetry, line scans, and area scans. By getting a better understanding of the electrochemical behavior of IPMCs, the soft actuator could be designed to enhance its capabilities of actuation.

10163-19, Session 5

IPMC-driven thrust generation: a new conceptual design

Zakai Olsen, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Ionic Polymer-Metal Composites (IPMC) are highly functional actuators that find many uses in the field of soft robotics due to their low actuation voltage and ability to operate in aquatic environments. The actuation of an IPMC relies on the swelling of the negatively charged side when a potential is applied, due to the free-moving cations and water molecules migrating to that half. While this bending type actuation can be utilized to perform many tasks, it is ill suited for the primary propulsion mechanism in certain soft robotic applications. Here, a new conceptual design is presented which utilizes the bending of IPMC materials to achieve complex actuation motion in an attempt to generate a non-zero net thrust for propulsion of soft robots. The design capitalizes on advances in the manufacturing processes of electroactive polymer materials, which now allow for more complex shapes and thus new and unique modes of actuation. By utilizing the consistent bending deformation of IPMC actuators, in conjunction with carefully considered geometry, an IPMC driven body may serve as a primary mode of propulsion through a positive net thrust generation. This work consists of the initial feasibility study, concept testing, and optimization for such an actuator through computer modeling and simulation. COMSOL will be used for the finite element analysis to design the most efficient and optimized design for a positive net thrust generation. Such an IPMC design may find a great deal of applications, and the potential of future integration into other soft robotic systems is considered.

10163-20, Session 5

A model framework for actuation and sensing of ionic polymer-metal composites

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Ionic polymer-metal composite (IPMC) is a promising material for soft-robotic actuator and sensor applications. This material system offers large deformation response for low input voltage and is suitable for operation in hydrated environments. Researchers have been developing IPMC actuators and sensors for applications with examples of self-sensing actuators, artificial fish fins and biomimicry of other aquatic lifeforms, and in medical operations such as in guided catheter devices. IPMCs have been developed in a range of geometric configurations, with tube or cylindrical and flat-plate rectangular as the most common shapes. Several mathematical and physics-based models have been developed for describing the transduction effects of IPMCs. In this work, a concise physics-based modeling framework is presented for actuation and sensing transduction in IPMC devices. This model backbone is primarily based on ion-transport and solids mechanics physics. Additionally, this model encompasses variable electrode properties. The modeling framework can also be used to predict cases of back-relaxation in DC actuation of IPMCs using a modified force coupling equation. Example applications of the modeling framework are presented. Simulation results are presented in comparison to experimental and are in good agreement.

10163-21, Session 5

A theoretical framework for the study of compression sensing in ionic polymer metal composites

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Ionic Polymer Metal Composites (IPMCs) are an emerging class of electroactive material, which typically consist of an ion-exchange polymeric membrane plated between within noble metal electrodes. Their complex electrochemomechanical response can be leveraged toward the design of sensors and artificial muscles, whereby an imposed mechanical deformation generates a voltage across the electrodes, and, vice versa, an imposed voltage causes deformation. While most of the technical literature has focused on bending deformations, there is empirical evidence of IPMCs' ability to sense through-the-thickness deformations ("compression sensing"). Here, we seek to explain the physics of compression sensing by establishing a new predictive modelling scheme, grounded upon a rigorous, thermodynamically-consistent electrochemomechanical continuum theory. Within this theory, the finite deformation mechanics is coupled with the modified Poisson- Nernst-Planck system, governing IPMC electrochemistry. We model IPMC compression sensing as a one-dimensional problem, for which we establish a perturbative closed-form solution to help elucidate IPMC physics and inform the design of compression sensors. This solution is derived by appropriately linearizing the governing equations and applying the method of matched asymptotic expansions to closely reconstruct the counterion concentration and electric potential at the polymer-metal interfaces. Finally, we demonstrate the predictive capabilities of the model through critical comparison with experimental results in the literature on dynamic deformations of Nafion-based IPMCs.

10163-94, Session PMon

Fabrication of dielectric elastomer stack transducers (DEST) by liquid deposition modeling

Florian Klug, Susana Solano Arana, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

The established fabrication methods for dielectric elastomer stack transducers (DEST) are based on two-dimensional thin-film technologies. That's why available DEST are based on simple shapes. For some applications, like valves or braille displays, this form is well suited, but an adaption to other applications comes along with difficulties and further process steps. Fabrication methods with the possibility of three-dimensional structuring would allow new applications and fast prototype production of individually suited DEST for each application. Furthermore, it allows the integration of electrical connections, cavities, channels, sensor and other structural elements during the fabrication.

In this work, a novel manufacturing system has been developed. It enables the production of multilayer and three-dimensional structured DEST by liquid deposition modeling. The system is based on a dual extruder, connected to a three-axis positioning system and allows a computer controlled liquid deposition of two materials. It has been shown, that with well-selected parameters the production of thin layers less than 50 μm and stacking electrode and dielectric materials is feasible. Finally, a first DEST with dielectric layer thicknesses less than 50 μm has been successfully demonstrated.

10163-95, Session PMon

Boundary-condition analysis for physics-based modeling of ionic-polymer-metal-composite electroactive polymers

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Physics-based modeling of ionic-polymer-metal-composite (IPMC), electroactive polymers is presented. IPMC actuation is highly time dependent and nonlinear, making for a process that is difficult to model. A new methodology for establishing and applying boundary conditions to the ionic flux within the samples, which is the root cause behind the actuation, is discussed, as well as the development of the corresponding flux- and sample-strain equations. Empirical results using poly(ethylene oxide)-based IPMCs were fitted under various conditions, including: ionic concentration, applied voltage, and testing temperature and returned a favorable average adjusted-R2, goodness-of-fit, of 0.987%, 0.994%, and 0.992%, respectfully.

10163-96, Session PMon

Sensitive plant leaf-like actuating of homogenous polyimide blend in response to water gradient

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Although the swelling or bending of hygroscopic polymers and their composites is common, the self-folding of a homogeneous polyimide (PI) film in dry state was seldom been reported. A free-standing and nonionic PI film could sensitively fold in response to the water gradient across the film and immediately return to its original state upon the removal of the stimulus. Both the water absorption amount and the stiffness of the polymeric network significantly affect the shape and style of the folding in response to water vapor. As PI blended with sulfonated-polyaniline (PANI-S), the sensitivity of the humidity-driven actuation was improved. The most unique part of this film is that very small amounts of water gradients across the film are sufficient to trigger the reversible folding and unfolding movements. The presence of PANI-S increased the water absorption amounts and created unique microstructure within the polymeric network. Consequently, the exchange of water molecules in the outmost layer of the film with those in the environment was accelerated and produced fast elastic deformation. The robust PANI-S/PI film can be patterned to grab, lift and release objects or fold into 3D structures. The lifetime of this actuator is at least 20 cycles. This tough polymeric actuator is a potential candidate and can be fabricated into any shape or on various substrate for various industrial applications.

10163-98, Session PMon

Proposal of a peristaltic micropump using dielectric elastomer actuators fabricated by MEMS technology

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A peristaltic micropump using dielectric elastomer (DE) actuators is proposed and developed. The peristaltic micropump is designed so that diaphragm-type DE actuators are placed serially on a microchannel and volume changes of each diaphragm-type DE actuator transfer fluid and pressure. In this report, we propose a novel MEMS process that enables us to place multiple DE actuators on the microchannel.

In order to fabricate a DE actuator using a MEMS technology, ultra violet (UV) curable materials for both compliant electrodes and DE are selected. For the compliant electrodes, poly (3, 4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) is used. The PEDOT:PSS is a polymer mixture of two ionomers and a conductive, transparent polymer. In this research, a UV curable property is added to the PEDOT:PSS selected. For the DE, polydimethylsiloxane (PDMS) is used. The PDMS is a silicon-based organic polymer and is widely used for the DE. In this research, UV curable PDMS is selected.

In order to verify the proposed fabrication process, we developed a diaphragm-type DE actuator using UV curable PDMS and PEDOT:PSS. The DE actuator is a disk shape with 10 mm diameter and 0.8 mm thick. In the developed fabrication process, a diaphragm-type DE actuator is fabricated in the order of (1) a bottom cover, (2) a bottom compliant electrode, (3) a DE, (4) a top compliant electrode, and (5) a top cover using UV curable material patterning.

In the driving experiment, an out-of-plane displacement of 55 μm was measured when 2.5 kV was applied to the DE actuator.

10163-99, Session PMon

Study on simplification of a multi-physical model of IPMC sensor generating voltage as sensing signal

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Ionic polymer-metal composites (IPMCs) generate electrical potential under deformation. IPMC sensors are expected to be applied in a wide range of fields, such as medical and welfare.

There have been several researches on modeling of IPMC sensors. Recently, Zhu et al. have proposed a sensor model which describes redistribution of cations and water molecules and electrical potential under a bending deformation. The model is characterized by focusing on the significance of water transport; however, the model is represented by a set of nonlinear partial differential equations (PDEs). In this paper, we simplify this complex PDEs to a set of low order linear ordinary differential equations (ODEs).

Firstly the nonlinear terms of the PDE model are approximated as linear terms. Then we solve the approximated linear PDEs with the method of separation of variables in order to get ODEs. In the separation of variables, spatial functions are approximated with admissible functions. We carry out simulations with both the PDE model and the obtained ODE model, and compare the results for validating the obtained ODE model. We use a finite element analysis software, COMSOL Multiphysics, to simulate the PDE model, and use MATLAB for the ODE model. Regarding the redistribution of water molecules and the generated voltage, the result of the ODE model shows a good agreement with the result of the PDE model. Regarding the redistribution of cations, the ODE model cannot simulate the redistribution of cations due to the selection of the admissible function.

10163-100, Session PMon

Experimental verification of displacement control on integrated ionic polymer-metal composite actuators with stochastic on/off controller

Keishiro Kimura, Norihiro Kamamichi, Tokyo Denki Univ. (Japan)

An ionic polymer-metal composite (IPMC) actuator is one of polymer-based soft actuators. It is produced by chemically plating gold or platinum on both surface of a perfluorosulfonic acid membrane which is known as an ion-exchange membrane. It is able to be activated by a simple driving circuit and generate a large deformation under a low applied voltage (0.5-3 [V]). However, individual difference and characteristics changes from environmental conditions should be considered for realizing a stable or precise control. To solve these problems, we applied the stochastic ON/OFF controllers to the integrated IPMC actuators with parallel connections. The controller consists of a central controller and distributed controllers. The central controller broadcasts a control signal such as an error signal to distributed controllers uniformly. The distributed controllers switch the ON/OFF states based on the broadcasted signal stochastically. The central controller dose not measure the states of each IPMC actuator, and the

control signals is calculated by using the output signal of the integrated actuator and reference signal. The validity of the applied methods was investigated through numerical simulations and experiments. The integrated IPMC actuator consists of 24 pieces IPMCs with connecting in parallel and input voltage is 2 [V]. The results show that it is possible to the control of displacement.

10163-101, Session PMon

Effect of porosity of the electrodes on ionic electroactive polymer actuators

Sunjai Nakshatharan Shanmugam, Urmas Johanson, Andres Punning, Alvo Aabloo, Univ. of Tartu (Estonia)

Ionic electroactive polymer (IEAP) actuators with carbon based porous electrodes and ionic liquid electrolyte are attractive alternatives compared to the actuators composed of noble metal electrodes. Besides of numerous other parameters, the porosity of the electrode matrix has high influence on the electrochemical behavior and mechanical response of these actuators. Porosity has direct influence on the tortuosity, electronic conductivity, ionic conductivity, ion diffusivity, mobility, as well as the specific area and specific capacitance of electrode. It can also influence directly the mechanical properties of the IEAP laminate: durability, stiffness, etc.

In this study, a detailed physical model that incorporates porosity of electrodes and its relation to the electrochemical, transport and mechanical behavior of the IEAP actuator is developed. The behavior of the actuator under different porosity values is investigated through finite elements simulation. The outputs of the simulation are potential drop, electrode and electrolyte current density, double layer charging and deformation of the actuator etc. Altering porosity and determining its optimum value help to comprehend the occurring physical and electrochemical processes, as well as to design actuators capable of delivering optimum electrical and mechanical response.

10163-103, Session PMon

Position control of twisted and coiled polymer actuator using a controlled fan for cooling

Kentaro Takagi, Takeshi Arakawa, Jun Takeda, Nagoya Univ. (Japan); Ken Masuya, Kenji Tahara, Kyushu Univ. (Japan); Kinji Asaka, National Institute of Advanced Industrial Science and Technology (Japan)

Recently, artificial muscles made of fishing lines or sewing threads, namely twisted and coiled polymer actuators (TCPAs), have been proposed by Haines et al. A TCPA contracts by applying heat and returns to its initial length by cooling. A TCPA can be driven by voltage if the TCPA is plated by metal or if conductive wire such as nichrome is wound around it. Compared with the conventional electroactive polymers, Advantages of TCPAs are low cost, simple structure and large actuation strain/force. However, a big disadvantage of TCPAs is slow response due to heat transfer. The problem becomes apparent during cooling, although the response of heating can be improved by feedback control.

This paper proposes a control method of switching heating and cooling. In the proposed method, a TCPA is cooled by an electric cooling fan. When the TCPA is heating, the cooling fan is stopped. In a previous report, the response speed can be improved by keeping cooling fan always on; however, unnecessary energy consumption is required even during heating. In the proposed method, energy consumption during heating does not increase and the response speed can be improved using fan only during cooling. The proposed control law is as follows. Firstly, the desired control input is determined by PI-D control with respect to the length of the actuator. Then, the control inputs to the heater and to the cooling fan are switched according to the sign of the PI-D controller output. The effectiveness of the proposed control method is demonstrated by comparing the cases with and without the cooling fan in the experiments.

10163-104, Session PMon

Elastic actuation for legged locomotion

Chongjing Cao, Andrew T. Conn, Bristol Robotics Lab. (United Kingdom)

Legged animals exploit compliance and elastic energy storage to minimize cost of transport and maximize stability, without the need for excessively complex high level control. While some notable examples exist of legged robots that have achieved such dynamic behaviour, their actuation systems incur limitations including complexity and scalability. Emergent soft robotic technologies such as dielectric elastomers (DEs) offer large actuation strains that are comparable to biological muscle and are inherently elastic. Such character is ideal for mimicking the natural muscle and tendon systems. This study investigates the feasibility of utilizing dielectric elastomer actuators (DEAs) to achieve dynamic locomotion by developing a DEA driven hopping leg. In this paper, two DEA configurations are adopted: bowtie and double cone, DEA models are proposed to describe the stroke and force output of the two configurations as a function of driving voltage. Two DEA models are found capable of predicting the performance of corresponding actuators accurately. Double cone design is proven to be superior to bowtie design in terms of ease of manufacturing, stroke and force output, stability, lifespan and natural antagonistic configuration. Prototype single layer cone DEAs were fabricated using VHB 4905 and the optimized design is able to produce maximum 1.2 N force output and ±10 mm stroke with dimensions of 35 mm (strut length) and 40 mm (frame inner diameter). Payload testing shows that this prototype is capable of lifting up to 210 g of mass (comparing to 10 g DEA mass). Telescope-prismatic and three segment leg configurations with the knee joint actuated by cone DEA are proposed and prototypes developed. Both simulation and experiment show that single leg hopping is unfeasible with VHB based actuators due to the high viscous loss, which suggestions that VHB is perhaps not the right material in performing dynamic locomotion actuation.

10163-105, Session PMon

Fabrication of sulfonated carbon nanotube/metal composite electrode based ionic polymer metal composite actuator

Jie Ru, Xi'an Jiaotong Univ. (China); Yanjie Wang, Hohai Univ. (China); Hualing Chen, Xi'an Jiaotong Univ. (China)

Ionic polymer metal composite (IPMC), a new kind of smart material, with remarkably large strain and stress under low-voltage stimulation, has been extensively studied in recent years, and also has taken much attention as suitable candidates for the next generation actuators, medical devices and micro air vehicles. In this paper, sulfonated carbon nanotube (SCNT) was synthesized and doped into Nafion matrix to prepare SCNT/Nafion composite films by casting method firstly. After that, a new kind of IPMC actuator was fabricated by sandwiching a Nafion film between two SCNT/Nafion composite films by hot-pressing method, and then plated palladium (Pd) electrode on the surface to overcome some major drawbacks of conventional IPMC actuators. Subsequently, several key parameters of the IPMC actuators were revealed and the morphology of the electrode and the cross-section were observed by scanning electron microscopy. Finally, the effects of the SCNT and the morphology of the composite electrodes on the electromechanical properties of IPMC actuators were evaluated experimentally and analyzed systematically. The results showed that the incorporation of SCNT into the electrode films greatly increased the penetrated electrode depth and significantly improved the electromachanical and electrochemical performances of IPMCs for realistic applications. It can be concluded that the novel method to prepare IPMC

actuators with carbon/metal composite electrode was effective and convenient

10163-107, Session PMon

Temperature-responsive carbon nanotube yarn artificial muscle

Hyunsoo Kim, Seon Jeong Kim, Hanyang Univ. (Korea, Republic of)

The temperature indicators or sensors has been developed for lifesaving vaccines, and various medical fields as showing the color changes. Currently, polydiacetylenes (PDAs) have been studied as chromatic sensors or temperature indicators due to their phase transition that is accompanied by a color change from blue to red. Therefore, PDAs were mainly used as counterfeit materials (bills, and gasoline), and bio, photonics, and temperature sensors due to phase transition occurs various stimuli, such as thermally, chemically, electrically stimuli. However, we focus on the structural change based on the polydiacetylene phase transition at low temperature using a copolymer composed of PDA in a multi-walled carbon nanotube (MWCNT) coiled yarn for a temperature-responsive tensile actuator. Instead of focusing on the general color change phenomenon of PDA, herein demonstrate the volume change of PDA in the MWCNT coiled yarn at low temperature provides high tensile strain. The insertion of the pluronic copolymer into the PDA/MWCNT coiled yarn caused the decreasing of the tensile actuation temperature when compared to an actuator without pluronic copolymer. The benefits of a MWCNT coiled yarn actuators with PDA-pluronic copolymer is that can be easily prepared, have a large tensile actuation, and are actuated at low temperature and it can be used as more useful temperature indicators or latching devices for preventing the opening of bottle lids which contain denaturalized medicine, food, and proteins.

10163-108, Session PMon

A biomimetic polymer actuator based on blend membrane of polyethylene oxide and nafion

Jie Ru, Xi'an Jiaotong Univ. (China); Yanjie Wang, Hohai Univ. (China); Hualing Chen, Xi'an Jiaotong Univ. (China)

A novel electro-active polymer actuator based on the biocompatible blend membrane of polyethylene oxide (PEO) and Nafion was developed to overcome some major drawbacks of the traditional Nafion ionic polymer-metal composite (IPMC) actuators. The main drawback of the Nafion-IPMC actuators was the straightening-back and relaxation caused by the dissipation of water under the constant voltage stimulus. The blend of PEO into Nafion matrix significantly increased water uptake ration of the membrane and greatly overcomed the relaxation of the Nafion-IPMC actuator under the constant voltage stimulus. The current actuator also showed much higher response rate than that of the Nafion-IPMC actuator. Under simple harmonic excitation, the peak-to-peak displacement was comparable to that of the Nafion-IPMC actuator. The excellent electromechanical performances of the novel actuator may be attributed to the unique hydrophilic nano-channels of the blend membrane. The actuator based on the blend membrane of PEO and Nafion can be a promising candidate for the next generation actuators, medical devices and micro air vehicles.

10163-109, Session PMon

Compact 5 kV high-voltage power supply for dielectric elastomer actuators

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

We have developed a compact and low-cost single-channel high-voltage power supply (HVPS) for driving dielectric elastomer actuators (DEAs). The hardware and software have been released as an open source project for other laboratories to use, adapt and improve. Commercial high voltage power supplies are often bulky, expensive, and not well suited to drive small capacitive loads at high voltage. Furthermore, most high-precision laboratory HV DC power supplies cannot rapidly switch on/off and therefore are unable to generate a square signal above a few mHz. Our HVPS has been specifically designed to drive DEAs at high frequencies with simplicity and portability in mind. We have designed several models with maximal voltages between 5kV and 1.2kV. Their output voltage is controllable to 1% of full scale, and The output voltage slew rate is higher than 15V/us, making it possible to generate high voltage square signals from 1mHz to more than 1kHz. The HVPS has a footprint of 130x65x30 cubic mm, and all the required components can easily be sourced for a total price under USD 450. The HVPS can be controlled via USB with the provided graphical user interface or a library of LabView VIs. The graphical user interface makes it easy to use all of the functions of the HVPS without the need for programming, whereas the LabView library makes it possible to customise the interface and integrate the supply with other instruments, for example to synchronize the driving of a DEA with a data acquisition system.

10163-110, Session PMon

Energy harvesting by dielectric elastomer generator and self-priming circuit: verification by radio transmission

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This paper discusses energy harvesting and its application using dielectric elastomer and self-priming circuit. With the self-priming circuit attached to the dielectric elastomer, the generated voltage increases exponentially according to the variation of the capacitance caused by applied deformation to the elastomer. Two-stage self-priming circuit is selected for optimal harvesting. The harvesting technique is able to increase the voltage of the dielectric elastomer from a few volts to kV order, however in this paper the generated voltage is limited up to 1kV not to break the dielectric elastomer. The ability of energy harvesting using dielectric elastomer and self-priming circuit is confirmed by both numerical simulation using LTSpice and experiments. In the experiment, the dielectric elastomer is deformed by an electric motor, and the harvested energy is stored to a charging capacitor through Zener diodes. A low-power microcomputer which has radio transmitter is connected to the charging capacitor for the application of energy harvesting. The experimental results show that it is possible to transmit the temperature data only by the power obtained from energy harvesting. In addition, by comparing the generated power with the charged power, the efficiency of the energy harvesting is calculated.

10163-111, Session PMon

Nickel-based flexible, wireless, and self-propelling micromotor

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For the practical realization of wireless micro/nano devices, the chemically powered, autonomous and self-propelled micro/nano machines are highly desirable. The self propulsion is mainly due to the conversion of chemical energy into mechanical force. There are several micromotors made up of Pt, Ag and enzymes etc., but they suffer from either economical or environmental point of view. In this work, we will present a wireless

self-propelling nickel based micromotor. The nickel flexible electrode is fabricated by polymer assisted metal deposition process and its stability is further enhanced by electrochemical deposition of polyaniline (PANI). This PANI coated nickel flexible electrode along with electrodeposited MnO2 layer decomposes H2O2 to oxygen in pH-5.5 citrate buffer solution and showing mobility based on bubble propulsion mechanism. The electrodeposition of MnO2 was performed by cyclic voltammetry from the aqueous solution of MnSO4 at pH-1.8. The oxygen evolution of nickel flexible electrode in H2O2 solution produce enough bubbles on its surface that propels the electrode. During this reaction, H2O2 was first adsorbed on the active sites of the MnO2 surface, then the MnO2 is reduced by H2O2 to Mn2O3 and Mn(OH)2 with the evolution of oxygen. Then Mn2O3 and Mn(OH)2 will be oxidized back to regenerate MnO2 by H2O2. The simple and cost effective preparation methods and also the movement in pH solution similar to physiological conditions make this system more attractive.

10163-112, Session PMon

Micromixer based on dielectric stack actuators for medical applications

Susana Solano Arana, Florian Klug, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

Based on a previously developed microperistaltic pump, a micromixer made out of dielectric stack actuators is proposed. The micromixer will be able to mix two fluids at a microscale, pumping both fluids in and out of the device. The device consists of three chambers. In the first and second chamber, fluids A and B are hosted, while in the third chamber, fluids A and B are mixed. The fluid flow regime is laminar.

The application of voltage leads to an expansion of the actuators in the z axis direction. This makes a channel open through which the fluids flow. The frequency of the actuation of the different actuators allows an increase of the flow rate.

The micromixer can be used for applications such as drug delivery and synthesis of nucleic acids, the proposed device will be made of Polydimethylsiloxane (PDMS) as the dielectric and graphite powder as the electrode material. PDMS is a biocompatible material, widely used in the prosthesis field. Mixing fluids at a microscale is also in need in the lab-on-a-chip technology for complex chemical reactions.

Using simulation software the micromixer is optimized to obtain the maximum flow rate and back pressure. The size and geometry of the actuators, the number and thickness of the layers are under study.

10163-113, Session PMon

IPMC-driven ciliary motion

Michelle Quizon, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Ionic polymer-metal composites (IPMCs) are valuable smart materials in biomimetics due to their low driven voltage, high force response, and easy customizability. An IPMC bends in response to an applied electrical field and the corresponding mobility of cations in the polymer network. The consistent bending deformation of an IPMC makes it an excellent candidate for the patterned motion of natural cilia. Modern manufacturing processes allow IPMCs to now be more easily shaped and sized, also. Mimicking the thin design and metachronous stroking motion of natural motile cilia lends to advantageous applications for synthetic particle delivery and more applicable to our other ongoing laboratory projects, movement of miniature aquatic soft robotics. This research is focused on replicating cilia structure and motion with IPMCs.

This work is a preliminary project for an effective set of artificial cilia to move miniature soft robotics. It consists of the comparison between our smart model designed with IPMCs to a simple mechanical model designed with typical metal alloys, concept testing, optimization through computer modeling, and evaluation of our smart model to previous research of dynamic parameters.

10163-114, Session PMon

Theoretical consideration of fishing wire artificial muscle

Robert Hunt, Qi Shen, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States); Il-Kwon Oh, KAIST (Korea, Republic of)

Coiled nylon fishing wire actuated by heat is being investigated both experimentally and theoretically. Coiled nylon is of great interest due to its Negative Thermal Expansion(NTE) property, that is, it contracts in the axial direction and expands in the radial direction when heated above glass transition temperature. Additionally, nylon is easily manufactured and an inexpensive material. By inducing a coil in the fiber through a twisting motion and applying heat, the nylon is capable of producing high specific power, stroke and actuation with little hysteresis. The nylons mean of contraction is mainly due to the temperature dependent bias angle, the angle between the coil and the axial direction, change which in turn affects the pitch of the coils. As the temperature of the nylon increases, the bias angle decreases and consequently the pitch length also decreases causing the overall contraction of the coil in the axial direction. To further capture the physics of the nylon, an analytical model of the coiled nylons actuation is being developed and validated through experimental work. The torsional stroke, stress, displacement and bias angle will be measured as a function of temperature. Fluid convection and joule heating will be the devices for heating the nylon. The nylon will be submerged in water and subjected to a convectional heater for the fluid convection and plating with an electrode is used for joule heating. The resulting data of the experiments will then be compared to the analytical model and the most viable heat treatment will be discussed.

10163-115, Session PMon

Effects of ionic liquids on the performance of IPMC

Changwoon Nah, MinJung Kim, Sangwoo Park, Joohye Won, Chonbuk National Univ. (Korea, Republic of)

One of the issues in operating the IPMC actuators in air condition is the limited lifetime due to the evaporation of aqueous electrolytes like water. Several attempts were already made for solving the problem using an ionic liquid (IL) with higher boiling point. In this study, three different ILs having similar boiling point but different molecular weight were employed in the IPMC actuators. The actuation performance, notably speed and lifetime, were measured and they are compared with that of water-based IPMC actuator. The lower molecular weight IL showed a comparable actuation speed of water due to faster movement of the ion cluster. The lifetime of the water-based IPMC actuator was found to be only 3 days. However, the IL-based IPMC actuators showed much improved service life.

10163-116, Session PMon

A type of uncooled infrared detectors based on PZT/ P(VDF-TrFE) nanocomposites

Guanghua Hou, Harbin Institute of Technology (China)

The pyroelectric composite materials which are based on ceramic and polymer and have the merit of ceramic and polymer, is the research hotspot in pyroelectric materials. Pyroelectric composite materials have low pyroelectric property, poor interface bonding and low polarizability of ceramic phase. In order to solve the problem, this thesis conducted a systematic research on improving of P(VDF-TrFE), modifying of interface, Then a new type of uncooled infrared detectors with polyimide substrate as the thermal isolation structure was prepared.

For the solution of the problem that P(VDF-TrFE) has low dielectric constant and conductivity, the piezoelectric ceramic transducer(PZT) was added. The impact of PZT content on the phase transformation, conductivity, pyroelectric property formation mechanisms were discussed. The results showed that with the addition of SWCNTs the beta phase was induced, the crystallinity and dielectric constant was increased.

With a view to solve the problem that the interface bonding between ceramic phase and matrix was poor, The PE-4430 and Tween-80 were added to improve the interface and property. The impacts of interfacial modifier content on the interface, crystallinity, breakdown strength, dielectric, piezoelectric and pyroelectric properties were discussed. The results revealed that with the proper content of interfacial modifier, the piezoelectric and pyroelectric properties were increased.

Finally, a type of uncooled infrared detectors with polyimide substrate as the thermal isolation structure was prepared. The bottom electrode and back electrode leader were prepared on the polyimide substrate by direct-writing. Then the bottom electrode and back electrode leader was connected via hole by laser micro cladding technology. Finally, the pyroelectric composite materials and top electrode were prepared by screen-printing technology on the bottom electrode, laying the foundation for small size and multi-elements based uncooled infrared detectors.

10163-117, Session PMon

Safe human robot interaction with a flexible tactile-proximity sensor using CMCs

Hyunyoung Shin, Hyo Seung Han, Tien Dat Nguyen, Hyouk Ryeol Choi, Sungkyunkwan Univ. (Korea, Republic of)

In this paper, a tactile-proximity sensor for Human-Robot Interaction (HRI) is presented. We proposed and demonstrated a flexible tactile-proximity sensor using Carbon Microcoils (CMCs) for robot arm applications. The sensor consists of an island-like FPCB (Flexible Printed Circuit Board) electrode layer to compensate the tactile-proximity sensitivity and CMC dielectric layer covered on its top, which is dot cylindrical shape. An in-plane configuration, it brings to the sensor high robustness, high durability, and high sensitivity due to the CMC dielectric layer to protect and conduct to the electrode layer. CMCs are considered to form a complex LCR circuit in an elastomer sheet and its electrical property is changed when an object approaches or touches the sensor. The amount of CMCs mixed in the sheet is carefully chosen for maximizing the sensing performances before applied to fabricate the sheet. Two sensing modes are adopted according to the system requirement. The sensor uses capacitive sensing mode for tactile sensing and inductive sensing mode for proximity sensing. The sizes of the sensor are 32 mm x 32 mm and 80 mm x 80 mm. The taxel resolution of the sensor takes a place of 2 mm and has interpolated to 1 mm using a software. The sensor detected applied pressure up to 300 kPa and the distance of an object from 100 mm to the end-effector of manipulator where the sensor is taken a place.

10163-119, Session PMon

Experience-based learning on determining the frictional coefficients of thermoset polymers incorporated with silicon carbide whiskers and chopped carbon fibers at different temperatures

Edward Harrison, Mohammed Alamir, Naif Alzahrani, Ramazan Asmatulu, Wichita State Univ. (United States)

High temperature applications of materials have been increasing for various industrial applications, such as automobile brakes, clutches and thrust pads. The big portion of these materials are made out of the polymeric materials with various reinforcements. In the present study, high temperature polymeric materials were incorporated with SiC whiskers and chopped carbon fibers at 0, 5, 10 and 20wt.% and molded into desired size and shape prior to the curing process. These inclusions were selected because of their high mechanical strengths and thermal conductivity values to easily dissipate the frictional heat energy and sustain more external loads. The method of testing involves using a metal ramp with an adjustable incline to find the coefficients of static and kinetic frictions by recording time and the angle of movement at various temperatures (e.g., -10 °C and 50 °C). The test results indicated that increasing the inclusions made drastic improvements on the coefficients of static and kinetic frictions. The undergraduate students were involved in the project and observed all the details of the process during the laboratory studies, as well as data collection, analysis and presentation. This study will be useful for the future trainings of the undergraduate engineering students on the composite, automobile and other manufacturing industries.

10163-120, Session PMon

Experience-based training of engineering students on concretes reinforced by recycled carbon fibers

Cumhur Coskun, Eylem Asmatulu, Naif Alzahrani, Hatim F. Zeineddine, Vamsidhar R. Patolla, Wichita State Univ. (United States)

Fiber reinforcement increases many properties of the concretes, such as toughness, strength, abrasion, and resistance to corrosion. Use of recycled carbon fibers from industrial waste offers many advantages because it will reduce the waste, contribute the economy, protect natural resources and improve the property of structural units. The City of Wichita, KS is known to be “Air Capital of the World” where many aircraft companies have been producing aircraft, parts and components. Due to the superior properties of composites (e.g., light weight, low density, high impact resistance), they have been highly used by the aircraft industry. Prepreg is the most preferred combination of the fiber and resin due to the easy application, but it has a limited shelf life (e.g., three months to one year at most) and scrap has no use after all in the same industry. Every year tons of un-used prepreg or after use scrap are being collected in Wichita, KS. Recycling prepreg from the post-consumer waste offers great advantages of waste reduction and resource conservation in the city. Reusing the carbon fibers obtained from outdated prepreg composites for concrete reinforcement will offer double advantages for our environment and concrete structures. In this study, recycled carbon fibers of the outdated prepreg composites were collected, and then incorporated with concretes at different ratios prior to the molding and mechanical testing. An undergraduate student was involved in the project and observed all the process during the laboratory studies, as well as data collection, analysis and presentation. We believe that experience based learning will enhance the students' skills and interest into the scientific and engineering studies.

10163-22, Session 6A

DEMES rotary joint: theories and applications

Shu Wang, Zhaogang Hao, Mingyu Li, Bo Huang, Harbin Institute of Technology (China); Li Ning Sun, Soochow Univ. (China); Jianwen Zhao, Harbin Institute of Technology (China)

As a kind of dielectric elastomer actuators, dielectric elastomer minimum energy structure (DEMES) can realize large angular deformations by small voltage-induced strains, which make them an attractive candidate for use

as biomimetic robotics. Considering the rotary joint is a basic and common component of many biomimetic robots, we have been fabricated rotary joint by DEMES and developed its performances in the past two years. In this paper, we have discussed the static analysis, dynamics analysis and some characteristics of the DEMES rotary joint. Based on theoretical analysis, some different applications of the DEMES rotary joint were presented, such as a flapping wing, a biomimetic fish and a multi-legged walker. All of the robots are fabricated by DEMES rotary joint and can realize some basic biomimetic motions. Comparing with traditional rigid robot, the robot based on DEMES is soft and light, so it has advantage on the collision-resistant.

10163-23, Session 6A

Dielectric elastomer actuator for the measurement of cell traction forces with sub-cellular resolution

Samuel Rosset, Alexandre Poulin, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Alicia Zollinger, Michael Smith, Boston Univ. (United States); Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We report on the use of dielectric elastomer actuators (DEAs) to measure the traction force field of cells with sub-cellular resolution. The study of cellular electrochemical and mechanical response to deformation is an important area of research, as mechanotransduction has been shown to be linked with fundamental cell functions, or the progression of diseases such as cancer or atherosclerosis. Experimental cell mechanics is based on two fundamental concepts: the ability to measure cell stiffness, and to apply controlled strains to small clusters of cells. However, there is a lack of tools capable of applying precise deformation to a small cell population while being compatible with an inverted microscope (stable focal plane, transparency, compactness, etc.).

Here, we use an anisotropically prestretched silicone-based DEA to deform a soft (7.6kPa) polyacrylamide gel on which the cells are cultured. An array of micro-dots of fluorescent fibronectin is transferred on the gel by micro-contact printing and serves as attachment points for the cells. In addition, the fluorescent dots (which have a diameter of 2um with a spacing of 6um) are used during the experiment to monitor the traction forces of a single cell (or small cluster of cells). The cell locally exerts traction on the gel, thus deforming the matrix of dots. The position of dots versus time is monitored live when the cells are submitted to a uniaxial strain step. Our deformable bioreactor allows to measure the local stiffness of cells submitted to mechanical strain, and is fully compatible with an inverted microscope setup.

10163-24, Session 6A

Dielectric elastomer actuator with variable bending stiffness property based on interlaminar electrostatic chucking

Hiroya Imamura, Univ. of Washington (United States) and Nabtesco Corp. (Japan); Kevin Kadooka, Minoru Taya, Univ. of Washington (United States)

In recent years, dielectric elastomer actuators (DEA) have been investigated as artificial muscle for soft robots, thanks to their light weight, high energy density, and silent operation. Moreover, the low stiffness of the dielectric elastomer (DE) material allows DEA to exhibit large actuation strain. On the other hand, the intrinsic softness of DEA limits their blocking and holding force. Therefore, incorporating variable stiffness structures into DEA is necessary to leverage both large actuation strain, and large holding force from such actuators. This work describes the modeling, fabrication, and characterization of a variable-stiffness DEA (VSDEA) based on interlaminar electrostatic chucking. The VSDEA consists of a multitude of stacked multilayer unimorph DEA units, where each unit consists of a passive layer and one or more active DE layers whose expansion under applied voltage induces bending of the DEA unit. Adhesion between the DEA units is mediated by electrostatic attraction caused by opposite charges accumulating on the interfacial surfaces between each unit. The bending stiffness of the VSDEA is controlled by increasing or decreasing the charge on the interfacial surfaces; large deformation can be achieved when the unit interfaces are allowed to freely slip, and large holding force is realized when electrostatic chucking is applied. A claw actuator consisting of a multitude of VSDEA was developed to grip and lift a mass greater than the actuator's weight.

10163-25, Session 6A

Snap actuation of dielectric elastomer and hydrogel in soft smart structure and robot

Tiefeng Li, Xiangping Chen, Mingqi Zhang, Bangyuan Liu, Zhejiang Univ. (China)

Dielectric elastomer and hydrogels are widely used in soft active structure due to their large actuations. We investigate the behavior of DEAs interacted with soft structure and function as soft robot. Various structures can achieve different responses of the DEAs and responsive hydrogel actuated soft robot. In our experiment, the high voltage source can be compactly designed and distributed in the soft robot. Snap instabilities of the soft active material can be engineered to acutate the sturcuture and soft robot. To calculate the performances of the whole robot, we record the locomotions and actuating force during an operation cycle. We simulate the behavior of the soft structure with commercial software ABAQUS and compare the results obtained from the simulation and experiment.

10163-26, Session 6A

High speed torsional actuators

Seyed Mohammad Mirvakili, Massachusetts Institute of Technology (United States); John D. W. Madden, The Univ. of British Columbia (Canada); Ian W. Hunter, Massachusetts Institute of Technology (United States)

Creating a rotational motion has been of great interest for human since the invention of the wheel. Electric motors, diesel engines, molecular motors, etc. all create rotational motion using at least two body components (rotor and stator). Recently it is shown that by twisting fine carbon nanotube yarns as well as metallic niobium nanowire yarns torsional actuation can be created within only one body of material. The underlying mechanism is simply turning the tensile actuation of the yarns to torsional actuation by infiltrating the yarns with a guest material such as wax. The wax expands by almost 30% in volume and creates torsional actuation when the yarn is heated. One of the drawbacks of these torsional actuators is that their raw materials (CNT yarns, Nb nanowire yarns, etc.) are commercially not available. In this work we are proposing an alternative technique by using readily available shape memory alloy fibers such as NiTi. We have achieved torsional peak speed of more than 6,000 RPM with amplitude of more than 40 °/mm of fiber's length.

10163-27, Session 6B

Chemically pre-strained dielectric elastomer finite element analysis

Brittany A. Newell, Gary W. Krutz, Purdue Univ. (United States)

The applications and feasibility of utilizing dielectric elastomer electroactive polymers in the industrial and medical sectors has drastically increased

in recent years due to significant improvements in actuation potential, manufacturing, the introduction of new materials and modeling capabilities. One such development is the introduction of chemical pre-strain as a novel method of providing enhanced actuation through pre-load. This method has been shown to produce improved mechanical displacements with actuations over 0.5 mm and capable of producing over 0.9 mN of total force. The purpose of this study was to utilize finite element analysis to analyze the potential mechanical actuation of an industrial fluoropolymer with chemical induced pre-strain and validate the model with experiential results. The finite element analysis model was created using Comsol Multiphysics. The model utilized multiple energy conversions and modalities including electrostatics, Joule heating, and standard mechanical modeling and boundary constraints applied to a 2-D axisymmetric design. Material properties were incorporated with a 5th order Mooney Rivlin hyperelastic material fitting accounting for strain densities. The effects of specific inputs and properties were analyzed through application of a parametric sweep to the finite element analysis model. The model was solved using a MUltifrontal Massive Parallel sparse direct solver, MUMPS. Results generated from the finite element analysis showed similar trends to results produced experimentally. A sensitivity analysis on the result showed size had a 68.5% effect, thickness had a 44.1% effect, and voltage had a 27.8% effect on the generated actuation.

10163-28, Session 6B

Thermodynamics and instability of dielectric elastomer

Liwu Liu, Yanju Liu, Jinsong Leng, Tong Mu, Harbin Institute of Technology (China)

Dielectric elastomer is a kind of typical soft active material. It can deform obviously when subjected to an external voltage. When a dielectric elastomer with randomly oriented dipoles is subject to an electric field, the dipoles will rotate to and align with the electric field. The polarization of the dielectric elastomer may be saturated when the voltage is high enough. When subjected to a mechanical force, the end-to-end distance of each polymer chain, which has a finite contour length, will approach the finite value, reaching a limiting stretch. On approaching the limiting stretch, the elastomer stiffens steeply.

Here, we develop a thermodynamic constitutive model of dielectric elastomers undergoing polarization saturation and strain-stiffening, and then investigate the stability (electromechanical stability, snap-through stability) and voltage induced deformation of dielectric elastomers. Analytical solution has been obtained and it reveals the marked influence of the extension limit and polarization saturation limit on its instability. The developed thermodynamic constitutive model and simulation results would be helpful in future to the research of dielectric elastomer based high-performance transducers.

10163-29, Session 6B

Inherently pre-strained and self-healing elastomers: new generation of freestanding electroactuators

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Dielectric elastomers (DEs) are the leading technology for artificial muscles due to a favorable combination of large stroke, fast response, and high energy density. However, at large actuations, DEs are prone to spontaneous rupture from electromechanical instability. This shortcoming is currently circumvented by chemical or physical bracing, which increases bulk and rigidity of the total actuator assembly and leads to significant cutbacks in device efficiency and utility. Now, we present a molecular design platform for the creation of freestanding actuators that allow for large stroke (>300%) at low applied fields (<10 V μm-1) in unconstrained as cast shapes. This approach is based on bottlebrush architecture, which features inherently strained polymer networks that eliminate electromechanical instability and the need for bracing. Through accurate control of side-chain length and crosslink density, we obtained effective actuation properties on par with commercial actuators with the advantage of lighter weight, lower voltage operation, and ease of fabrication, which open new opportunities in soft-matter robotics. Furthermore, incorporation of dynamic reversible bonds ensures self-healing of rupture actuators.

10163-30, Session 6B

Super stretchable soft actuator by using twisted and coiled polyurethane fiber

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Twist and Coiled polymer Actuator (TCA), which is a new type of soft actuator, is simply fabricated by twisting a polymer fiber. Since TCA has high power-to-weight ratio, the actuator is expected to be utilized as an artificial muscle. In the previous researches, TCA was mainly fabricated with a Nylon 6,6 fiber, and Nylon-TCA showed strong force and large strain outputs. However, the useful force and strain were not much high in the repeatable and stable range. With arranging several TCAs in a parallel manner, the force output can be amplified. Using an additional device such as a transmission or a very long TCA can be solutions to increase the displacement from TCA, but these solutions cause complexity of fabrication and loss of softness. This paper introduces PU-TCA which is fabricated with a polyurethane fiber. With the previous fabrication process, it is impossible to fabricate PU-TCA. Therefore, a new fabrication method for PU-TCA has been developed. In order to evaluate the performances of Nylon-TCA and PU-TCA exactly, a TCA performance evaluation test-bed was also developed. Nylon-TCA and PU-TCA were fabricated under identical condition, and the performances were compared by using the test-bed. PU-TCA showed larger strain in a same payload, and it was actuated lower temperature than Nylon-TCA.

10163-31, Session 6B

Development of a fatigue testing setup for dielectric elastomer membrane actuators

Marc Hill, ZeMA GmbH (Germany); Gianluca Rizzello, Stefan S. Seelecke, Univ. des Saarlandes (Germany)

Dielectric Elastomers (DE) represent a transduction technology with high potential in industrial application, due to their low weight, flexibility, and small energy consumption. For industrial applications, it is of fundamental importance to quantify the lifetime of DE technology, in terms of electrical and mechanical fatigue, when operating in realistic environments. This work contributes toward this direction, by presenting the development of an experimental setup which permits systematic fatigue testing for DE membranes. The setup permits to apply both mechanical and electrical stimuli to the membranes, and measure at the same time their mechanical (force, deformation) and electrical response (capacitance, resistance). In its final state, the setup will allow to test up to 15 DE membranes at the same time for several thousands of cycles. The control of the modules, the monitoring of the actuators, and the data acquisition are realized on a cRio FPGA-System running with LabVIEW. The setup is located in a climate chamber, in order to investigate the fatigue mechanisms at different environmental conditions, i.e., in terms of temperature and humidity. The setup consists of two main parts, namely a fatigue group and a measurement group. The fatigue group stays permanently in the climate

chamber, while the measurement group is assembled to the fatigue group and allows to perform measurements at 20°C . This will permit to quantify mechanical and electrical failure mechanisms and to understand how they affect the lifetime of DE membrane actuators.

10163-33, Session 7A

3D printing PLA and silicone elastomer structures with sugar solution support material

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3D printing technology has been used for rapid prototyping since 1980's and is still developing in a way that can be used for customized products with complex design and miniature features. Among all the available techniques used by companies and researchers, Fused Deposition Modeling (FDM) is one of the most widely used technologies because of its capability to build different structure with many materials. However, there is still limited desktop 3D printers that can handle complex parts well due to the lack of a good solution for support. Support materials is one of the few solutions suggested for several complex geometries such as fully suspended shapes, overhanging surfaces and hollow features. Meanwhile, support materials can be employed even in simple desktop printers to expand the potential of printing. This paper describes an approach to 3D print a structure using silicone elastomer and polylactide fiber (PLA) by employing a support material that is soluble in water. This support material mainly consist of sugar and water which can easily be prepared by a low cost method. Sugar is a kind of carbohydrate which is found naturally in plants such as sugar cane and sugar beets therefore, it is completely organic and environmental and eco-friendly. As another advantage, the time for removing this material from the part is considerably less than other support materials which is commercially available and it can be removed easily by warm water without any part remains. The experiment has been done with a special novel set up on an inexpensive desktop 3D printer to fabricate complex structures for use in soft robots. The results envision that further development of this system would contribute to the way for fabrication of complex parts with lower cost yet high quality.

10163-35, Session 7A

Drop-on-demand printing of dielectric elastomer actuator electrodes

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We report a non-contact printing method to accurately pattern carbon-based electrodes on thin silicone membranes. To reduce the operating voltage of Dielectric Elastomer Actuator (DEA), the elastomer membranes are being made ever thinner. But printing on suspended 1 μm thick membranes is challenging because these membranes are fragile. Piezoelectric Drop on Demand (DoD) printing was chosen because it is a non-contact printing method which can deposit the electrode mixture in precisely dosed quantities at exact locations. However, producing an electrode mixture which can be printed is far from trivial. The electrode mixture must be jettable, compatible with the surface, and functional (stretchable, low stiffness, high conductivity). A mixture has been formulated which meets all of the above requirements, consisting of carbon black, a dispersant, and a solvent. We present the formulation of the electrode mixture and the jetting parameters required to print it. We fabricated a DEA device on a silicone membrane to characterise the properties of the electrode material and to demonstrate the performance of the printing technique, with which intricate electrode designs were printed. We report on electrode resistance vs. strain, Young's modulus, and actuation strain of the DEA. The techniques developed here are suitable for DEA of any thickness and can be used to produce high resolution electrodes for DEA with many functions.

10163-97, Session 7A

Permanent magnets as biasing mechanism for improving the performance of circular dielectric elastomer out-of-plane actuators

Philipp Loew, Gianluca Rizzello, Stefan S. Seelecke, Univ. des Saarlandes (Germany)

Dielectric Elastomers (DE) represent an attractive technology for the realization of mechatronic actuators, due to their lightweight, high energy density, high energy efficiency, scalability, and low noise features. In order to produce a stroke, a DE membrane needs to be pre-loaded with a mechanical biasing mechanism. In our previous work, we compared the stroke achieved with different biasing mechanisms for a circular out-of-plane DE Actuator (DEA), i.e., hanging masses, linear and bi-stable springs.

The novel contribution of this work is the investigation of a biasing design approach based on permanent magnets. Compared to previously investigated biasing solutions, the magnets permit to achieve an improved displacement and to increase the bandwidth of the actuator, with a reduced amount of hysteresis. Additionally, the resulting actuators based on magnet biasing is usually more compact than the spring-based ones, allowing to design more compact systems.

Two design solutions are proposed and compared, namely a first one characterized by a stable actuation, and a second one which permits to achieve a higher stroke, but is intrinsically unstable. The effectiveness of the novel design is assessed by means of several experiments.

10163-118, Session 7A

Ras Labs-CASIS-ISS NL experiment for synthetic muscle returned to Earth: resistance to ionizing radiation

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In anticipation of deep space travel, new materials are being explored to assist and relieve humans in dangerous environments, such as high radiation, extreme temperature, and extreme pressure. Ras Labs Synthetic Muscle™ – electroactive polymers (EAPs) that contract and expand at low voltages – which mimic the unique gentle-yet-strong nature of human tissue, is a potential asset to manned space travel through protective gear and human assist robotics and for unmanned space exploration through deep space. Gen 3 Synthetic Muscle™ was proven to be resistant to extreme

temperatures, and there were indications that these materials would also be radiation resistant. The purpose of the Ras Labs-CASIS-ISS Experiment was to test the radiation resistivity of the third and fourth generation of these EAPs, as well as to make them even more radiation resistant. On Earth, exposure of the Generation 3 and Generation 4 EAPs to a Cs-137 radiation source for 47.8 hours with a total dose of 305.931 kRad of gamma radiation was performed at the US Department of Energy's Princeton Plasma Physics Laboratory (PPPL) at Princeton University, followed by pH, peroxide, Shore Hardness durometer, and electroactivity testing to determine the inherent radiation resistivity of these contractile EAPs, and to determine whether the EAPs could be made even more radiation resistant through the application of appropriate additives and coatings. The on Earth preliminary tests determined that selected Ras Labs EAPs were not only inherently radiation resistant, but with the appropriate coatings and additives, could be made even more radiation resistant. G-force testing to over 10 G's was performed at US Army's ARDEC Labs, with excellent results, in preparation for space flight to the International Space Station National Laboratory (ISS-NL). Selected samples of Generation 3 and Generation 4 Synthetic Muscle™, with various additives and coatings, were launched to the ISS-NL on April 14, 2015 on the SpaceX CRS-6 payload, and after 1+ year space exposure, returned to Earth on May 11, 2016 on SpaceX CRS-8. The most significant change observed from the preliminary on Earth radiation exposure was color change in the irradiated EAP samples, which in polymers can be indicative of accelerated aging. There was visible yellowing in the irradiated samples compared to the control samples, which were not irradiated and were clear and colorless. Likewise, the flown EAP samples had visible yellowing compared to the ground control EAP samples. While the Synthetic Muscle Experiment was in orbit on the ISS-NL, photo events occur every 4 to 6 weeks to observe any changes, such as color, in the samples. Both the 32 flown EAP samples and 32 ground control samples were tested for pH, material integrity, durometer, and electroactivity, with very good results. The samples were also analyzed using stereo microscopy, scanning electron microscopy (SEM)), and energy dispersive X-ray spectroscopy (EDS). Smart electroactive polymer based materials and actuators promise to transform prostheses and robots, allowing for the treatment, reduction, and prevention of debilitating injury and fatalities, and to further our exploration by land, sea, air, and space.

10163-36, Session 7B

Design of high-frequency ultra-thin trilayer conducting polymer micro-actuators

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Fast actuation of conducting polymer trilayers has been shown by reducing the thickness of the device as small as 6 μm. Here we introduce an approach to design fast trilayers using three RC time constants (τ) of the equivalent electric circuit of the device. These time constants, and hence the working frequency, depend on the critical dimensions of the films of the trilayer actuator (width, length, conducting polymer thickness and separator thickness).

According to this method, full actuation of trilayer conducting polymers at frequencies well in excess of several hundreds of Hz is feasible by engineering the thickness of the conducting polymer down to sub-micrometer scales, while that of the separator is several micrometers. This fast response, however, is obtained at the expense of force and displacement generated by the actuators as predicted by the beam bending equations. Considering the importance of these parameters for different applications, we investigate the trade-off between the actuation speed and the force and the displacement generated by these trilayers.

We then extend our approach to other ionic electroactive polymer bending actuators such as Ionic polymer–metal composites (IPMC)s and Bucky gels, providing a useful tool for designers who want to take advantage of the low voltage and low weight of these soft actuators compared to conventional ones. Our approach is then evaluated by comparing the predictions obtained through this method with experimental results.

10163-38, Session 7B

Property modification of nafion via polymer blending with polyimide

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The blended ion exchange membrane between Nafion and Polyimide (PI) was used for fabrication of the ionic polymer–metal composite (IPMC) not only to redeem inherent drawbacks of Nafion such as high cost or environment-unfriendliness but also to enhance mechanical properties of Nafion. PI solution was blended in Nafion solution by a volume ratio and membranes were prepared through solution casting method. The prepared blended Nafion membranes can be fabricated IPMCs with electroless plating of platinum electrode onto its surface. The surface resistance of all prepared IPMCs is measured through 2-point probe. This study investigated the chemical structure and mechanical properties of prepared blended membranes. Moreover, we characterized the cross-section morphology and studied the electromechanical performances (displacement and blocking force) of prepared IPMC actuators. The prepared IPMC actuators with blended Nafion membranes were demonstrated comparable electromechanical performance by significantly reducing the content of Nafion.

10163-39, Session 7B

The highly stable air-operating IPMC actuator with consecutive and controlled channels generated by copper foam

Qingsong He, Zhigang Liu, Min Yu, Zhendong Dai, Institute of Bio-inspired Structure and Surface Engineering (China)

A highly stable air-operating IPMC actuator with consecutive and controlled channels, suitable for migration of cations and anions of ionic liquid, was prepared by introducing and removing copper foam in this work. The electro-chemical-mechanical properties of this novel porous IPMC were investigated. Scanning electron microscopy observation shows that the channels ranging from ~200 nm to 38 μm are distributed in the Nafion membrane. This porous IPMC was doped with 1-ethyl-3-methylimidazolium thiocyanate (EMImSCN) ionic liquid. Attenuated total reflection- fourier transform infrared spectroscopy (ATR-FTIR) was used to confirm the adsorption of EMImSCN in Nafion membrane. An electric double-layer is formed at the interface between the platinum electrode and the ionic membrane under the input potential, resulting in a higher capacitance. The suitable ion migration channels and large capacitance enable us to achieve high strain and excellent durability upon 5 h continuous air-operation.

10163-102, Session 7B

Temperature and humidity dependence of ionic electroactive polymer actuators

Sunjai Nakshatharan Shanmugam, Andres Punning, Alvo Aabloo, Univ. of Tartu (Estonia)

The ionic electroactive polymer (IEAP) actuators with carbonaceous electrodes and ionic liquid electrolytes are distinguished by their ability for operation in open air. Nevertheless, their behavior is influenced by at least two parameters of the ambient environment – temperature and humidity.

Both parameters affect many factors of the IEAP materials: viscosity and ionic conductivity of the electrolyte, specific capacitance of the electrodes, stiffness of the polymer, etc. This circumstance makes it difficult to comprehend the actual physical and electrochemical processes occurring in the IEAP materials as well as hinders the control of the actuators in the possible applications.

This work is focused on characterizing the temperature- and humidity-dependence of the electromechanical response and electrochemical impedance of IEAP actuators. An extensive experiment was performed with several types of IEAP actuators in a temperature- and humidity-controlled environment. The characterizations of electrical and electromechanical response as well as electrochemical impedance spectroscopy measurements were carried out at temperatures ranging from -20 ºC to +60 ºC and relative humidity ranging from 0% to 90%. The result showing that impact of both parameters on IEAP actuators is easily recognizable, while the relative humidity has more influential effect than temperature.

10163-40, Session 8A

Rate dependent constitutive behavior of dielectric elastomers and applications in legged robotics *(Invited Paper)*

William S. Oates, Paul Miles, Wei Gao, Jonathan Clark, Somayeh Mashayekhi, Mohammad Y. Hussaini, Florida State Univ. (United States)

Dielectric elastomers exhibit novel electromechanical coupling that has been exploited in a broad range of adaptive structure applications. Technology transition to robotic systems within our group has been supported by multiphysics constitutive model development, structural analysis, and experimental characterization. Whereas the quasi-static, one-dimensional constitutive behavior can often be accurately quantified by hyperelastic functions and linear dielectric relations, accurate predictions of electromechanical coupling during multiaxial loading is non-trivial. Moreover, viscoelasticity is difficult to predict over a broad range of deformation rates particularly during finite deformation processes. In this talk, an overview of multiaxial electromechanical constitutive behavior is analyzed and extended to rate dependent, nonlinear viscoelasticity. Bayesian uncertainty analysis is utilized to quantify material parameter uncertainty to judge the accuracy of different electromechanical constitutive relations and membrane approximations to illustrate how parameter uncertainty propagates to model predictions of stress, electric displacements, and membrane displacements as a function of applied strain and electric fields. Finally, this knowledge is transitioned to a legged robotic structure where large scale fatigue characteristics are experimentally quantified. Cyclic loading of a legged robotic structure is shown to reach over two million mechanical cycles. Degradation in the fatigue limit, as a function of field application, is also evaluated.

10163-41, Session 8A

Numerical investigation of chemically stimulated composite hydrogel-layers

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Stimuli-sensitive hydrogels are polymeric materials, which are able to reversibly swell in water in response to evironmental changes. Relevant stimuli include variations of pH, temperature, concentration of specific ions etc. Stacked layers composed of multiple thin hydrogels - also reffered to as hydrogel-layer composites - combine the distinct sensing properties of different hydrogels. This approach enables the development of sophisticated microfluidic devices such as bisensitive valves or fluid-sensitive deflectors.

In order to numerically simulate the swelling of a polyelectrolyte hydrogel in response to an ion concentration change the multifield theory is adopted. The set of partial differential equations - including the description of the chemical, the electrical and the mechanical field - are solved using the finite element method. Simulations are carried out on a two-dimensional domain in order to capture interactions between the different fields. In the present work, the ion transport is governed by diffusive and migrative fluxes. The distribution of ions in the gel and the solution bath result in an osmotic pressure difference, which is responsible for the mechanical deformation of the hydrogel-layer composite.

The realized numerical investigation gives an insight into the evolution of the displacement field, the distribution of ions and the electric potential within the bulk material and the interface between gel and solution bath. The predicted behavior of the relevant field variables is in excellent agreement with investigations and results available in the literature.

10163-42, Session 8A

Modeling and experimentally characterizing ionic buoyancy engines

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There is a need for buoyancy engines to modulate sensor depth for optimal positioning and station-keeping. Compared to current technologies, Ionic Buoyancy Engines does not have any moving parts. They are energy efficient and miniaturization ready. An Ionic Buoyancy Engine changes its density by locally varying ionic concentrations in a closed chamber with a wall made of a semi-permeable membrane such as Nafion. The local change in concentration pumps water in and out of the chamber leading to buoyancy change. This study presents a model that is used to simulate the steady state controlled depth of the buoyancy engine as a function of the local concentration of ions inside the engine's chamber. Furthermore experiments are performed to characterize the amount of water pumped in an out of the engine's chamber as a function of the electrode geometry and position, electric potential, and ionic concentration. For instance the engine displaced 95mm3 of water consuming 1.88J of electrical energy in 2hrs. The experimental data proved that the buoyancy engine retained 100% of its pumped water when the electrodes were opened for a duration of more than 5hrs.

10163-43, Session 8A

Dynamic instability of dielectric elastomer actuators subjected to unequal biaxial prestress

Atul Sharma, Dhanashri M. Joglekar, Manish M. Joglekar, Indian Institute of Technology Roorkee (India)

This paper outlines an energy-based approach for extracting the dynamic instability parameters (electric field and thickness stretch) of homogeneously deforming dielectric elastomer actuators subjected to an unequal biaxial prestress, and driven by a suddenly applied electric load. The approach relies on setting up the balance between the kinetic, strain, and electrostatic energy at the point of maximum overshoot in an oscillation cycle. Using the Hamiltonian approach, the aforestated statement of energy-balance leads to the equation of the stagnation curve. The condition of instability is then imposed for extracting the dynamic instability parameters of the actuator configuration. The underlying principles of the approach are elucidated by considering the Ogden family of hyperelastic material models. The approach is however portrayed generically, and hence, can be extended to the other hyperelastic material models of interest. The estimates of the dynamic instability parameters are corroborated by examining the saddle-node bifurcation points in the time-history response obtained by integrating the equation of motion. A parametric study is conducted to bring out the effect of unequal biaxial prestress, and the trends of variation of the critical electric field and the thickness-stretch at the onset of dynamic instability are presented. It is shown that the electric field corresponding to the dynamic

instability is lower than that corresponding to the static instability. In contrast, the maximum stretch experienced by the actuator at the dynamic instability is significantly higher than that at the static instability. The crucial inferences can find their potential use in the design of DEAs subjected to a transient motion.

10163-44, Session 8A

Numerical analysis of helical dielectric elastomer actuators

Saurabh Nair, Daewon Kim, Embry-Riddle Aeronautical Univ. (United States)

Dielectric elastomers actuators (DEA) are known for its capability of experiencing extreme strains under electric fields. Despite its numerous potential, the manufacturing process of DEA poses multiple restrictions on their performance. A helical DEA (HDEA) with its unique configuration does not only provide the contractile and extendable capabilities, but can also aid in attaining results for bending and torsion. This study focuses on the simulation of HDEA with helical compliant electrodes, prior to its application. Primarily for this investigation, both experimental and simulation models are analyzed and compared for stacked single and multi-layered DEAs. Specific actuation voltages are applied to these actuators to analyze their mechanical responses. Numerical analysis of the designed HDEA is conducted after conforming the accuracy of the model to known results. The attributes of the material used to build the structure plays a vital role in the behavior of the system. For numerical analysis, the material characteristics are input into a commercial grade software, then the appropriate strain analysis is performed for multiple response modes to retrieve its outcome. The properties of the materials are derived using a dynamic mechanical analyzer. Applying these characteristics into the simulation, the functionality of HDEA for various activations can be achieved. After generating results from numerical analysis, validation and testing can be conducted and compared with the fabricated prototype. The concept of HDEA embraces many new techniques and can be applied in multiple disciplines.

10163-45, Session 8A

Nonlinear vibration of dielectric elastomer incorporating strain stiffening

Fangfang Wang, Tongqing Lu, T. J. Wang, Xi'an Jiaotong Univ. (China)

Due to the strain-stiffening of polymer chains, a membrane of dielectric elastomer (DE) can reach two different stable equilibrium states under a static electrical load. In this paper, a theoretical model is developed to investigate the strain-stiffening effect on the nonlinear vibration of a circular DE membrane subjected to electro-mechanical loading. Free vibration, steady parametric excitation and chaos of the DE membrane undergoing large deformation are studied respectively. We find that after a small perturbation the DE membrane vibrates steadily around the two stable stretches and two natural frequencies exist for the same loading condition. With the increase of initial perturbation energy, the amplitude-frequency response of free vibration shows a transition from behaving like a soft spring to a hard spring attributed to strain-stiffening effect. When driven by a sinusoidal voltage, the DE membrane can resonate at multiple frequencies of excitation around small and large stable equilibrium states respectively. Variation of the sinusoidal voltage may induce a sudden change from steady vibration to chaos and the critical conditions for the transition are numerically calculated.

10163-46, Session 8A

Analysing trade-offs in the frequency response of dielectric elastomer generators

Plinio Rodrigues de Oliveira Zanini, Jonathan M. Rossiter, Martin Homer, Univ. of Bristol (United Kingdom)

Despite being a focus of research for some years, Dielectric Elastomer Generator (DEG) systems still do not have a standard design method. Most design processes aim at finding the right cycle and the best geometry for a given situation and performance, but with a single excitation frequency in mind. This limits the applicability of the design in real-world situations where forcing frequency is not constant as in, e.g., energy harvesting from ocean waves or human movement.

Since the energy output of a DEG cycle depends mostly on the change in stretch ratio between the charging and discharging phases, DEGs are claimed to have a broad spectrum of operating excitation frequencies. In principle, DEGs increase their power output as their excitation frequency increases, given that more cycles means the energy output will occur more often. On the other hand, material viscoelasticity will reduce the amplitude of the stretch cycle as frequency increases, as a consequence of material response to external forcing. Thus, we have a clear trade-off, suggesting that an optimum performance point exists.

Through the use of practical design scenarios we use modelling and simulation to determine the material response and, hence, carefully investigate the optimal excitation frequencies that maximise the performance (in terms of measures such as power output or efficiency) of DEGs and understand how to choose the parameters to optimise the DEG design.

10163-47, Session 8B

Hybrid carbon nanotube yarn artificial muscles powered by moisture

Shi Hyeong Kim, Tae Jin Mun, Seon Jeong Kim, Hanyang Univ. (Korea, Republic of)

There has been a current interest in developing self-powered hygromorph actuators driven by moisture from the ambient environment. In previously reported hygromorph muscles, there has been a limitation when it comes to bending or torsional motions or tensile actuators with low work and energy density. Herein, we developed a hybrid artificial muscle with a unique structure that combines with coiled and wrinkled structure. The hybrid muscle was fabricated by biscrolling technique, which is highly twisting carbon nanotube sheets that incorporated a hydrophilic polymer. When changing the relative humidity or by water contact, the muscle provided a high tensile stroke and gravimetric work capacity during contraction, and it was not significantly influenced in ambient temperature. When the diameter of hybrid muscle increased, the hybrid muscle provided roughly constant tensile contraction and work capacity. Also, the hybrid muscle showed the fastest contraction strain rate during absorbing water, comparing previously reported hygromorph tensile artificial muscles. While most of hygromorph bending or torsional artificial muscles are difficult to upscale, our tensile hybrid muscle showed easily upscale by configuring multiple muscles in parallel. The hybrid muscles were applied to an automatic ventilation system controlled by dew condensing and we expected that it could be adapted to control the desire relative humidity of an enclosed space.

10163-48, Session 8B

Electrospraying and ultraviolet light curing of nanometer-thin polydimethylsiloxane membranes for low-voltage DEA

Bekim Osmani, Tino Töpper, Florian M. Weiss, Univ. Basel (Switzerland); Gabor M. Kovacs, EMPA (Switzerland); Bert Müller, Univ. Basel (Switzerland)

Dielectric elastomer actuators (DEA) have attracted interest as actuators, sensors, and even as self-sensing actuators for applications in medicine, soft robotics, and microfluidics. To reach strains of more than 10 %, they currently require operating voltages of several hundred volts. In medical applications for artificial muscles, however, the operation is limited to a very few tens of volts. Electro-spraying is cost effective and allows upscaling using multiple nozzles for the fabrication of silicone films with nanometer thickness. Deposition rates of several micrometers per hour have been reached [1]. It has been recently demonstrated that DEA membranes with average sub-nanometer roughness can be fabricated by electro-spraying and subsequent ultraviolet (UV) light irradiation [2]. Here, we show a dimethyl silicone copolymer fluid that contains mercaptopropyl side chains in addition to the conventionally used methyl group substituent for the fabrication of the DEA membrane. Its elastic modulus was tuned with the irradiation dose of the 200 W Hg Xe lamp. We have also investigated the formation of the elastomer films using PDMS-concentrations in ethyl acetate of 1, 2, 5 and 10 vol %. After UV-light curing, the surface roughness was measured by means of atomic force microscopy. This instrument also enabled us to determine the average elastic modulus out of, for example, 900 nanoindentation measurements using a spherical tip with a radius of 500 nm. The elastomer films were cured during a period of less than one minute, a speed that makes it feasible to combine electro-spraying and in situ UV curing in a single process step for fabricating low-voltage multi-layer DEA.

[1] F.M. Weiss et al., Advanced Electronic Materials 2 (2016) 1500476.

[2] F. Weiss et al., Langmuir 32 (2016) 3276-3283.

10163-49, Session 8B

Leakage current and actuation efficiency of thermally evaporated low-voltage dielectric elastomer thin-film actuators

Tino Töpper, Bekim Osmani, Samuel Lörcher, Bert Müller, Univ. Basel (Switzerland)

The low-voltage operation is the key challenge for dielectric elastomer actuators (DEA) to enter the application field of medically approved actuators or sensors, such as artificial muscles or skin. Recently, it has been successfully shown that the reduction of the elastomer film thickness to a few hundred nanometers allows for the DEA operation reaching 10 % strain using a few volts [1]. Fabricated as multi-layer stacked nanostructures DEA are essential components for low-voltage operated adaptable lens systems, robotics and haptics. Molecular beam deposition (MBD) enables us to tailor elastomer films with acceptable defect level [2]. Combined with in situ spectroscopic ellipsometry, MBD is a unique method to reliably deposit polydimethylsiloxane (PDMS) thin films with nanometer precision. The homogenous cross-linking of the PDMS film has been in situ realized by curing through ultraviolet (UV) radiation during deposition. The surface morphology of the films was characterized using atomic force microscopy revealing smooth surfaces with sub-nanometer surface roughness. The understanding of leakage currents of such nanometer-thin elastomer films is crucial to preserve the unique actuation efficiency for DEAs in low-voltage operation. Leakage currents are determined with respect to the elastomer thickness ranging between 200 and 800 nm. An adhesion layer of thiol-functionalized PDMS is applied to localize gold particles of the electrode layer based on strong thiol-Au bonding. This is intended to prevent diffusion into the nanometer-thin elastomer film and to reduce the leakage current. Spectroscopic ellipsometry combined with cantilever bending is utilized for the characterization of these DEA low-voltage nanostructures regarding force, strain and actuation efficiency. A two-layer DEA nanostructure is compared to a single layer DEA with doubled elastomer film thickness to evaluate the repeatedly discussed stiffening electrode effect. This occurs when DEA nanostructures are stacked above hundreds of times, which is the future challenge to realize biomimetic DEA actuator with forces close to the natural muscles tissue.

[1] T. Töpper et al., Sensors and Actuators A 233 (2016) 32-41

[2] T. Töpper et al., APL Materials 4 (5) (2016) 056101

10163-50, Session 8B

Development of flexible electrodes from carbon nanotubes and polydimethylsiloxane

Titus M. Mulembo, Takahiro Nitta, Nagai Gakuji, Hirohisa Tamagawa, Sasaki Minoru, Gifu Univ. (Japan)

Development of high performance flexible electrodes can improve state-of-the-art of wearable displays, flexible phone screens and dielectric elastomer actuators.In recent times, carbon nanotubes (CNTs) and polydimethylsiloxane (PDMS) composites have gained popularity in the fabrication of flexible electrodes. This is because CNTs possess high aspect ratio and electrical properties unheard of in any other material. However, CNTs hardly mix well into PDMS and tends to aggregate into large bundles due to their relatively high surface energy. Poor dispersion and high aggregation limits attaining high conductivities for the flexible electrodes,which brings a serious hurdle in using CNTs for the flexible electrodes. In this research, non-covalent functionalization and dispersion of multiwalled carbon nanotubes (MWCNT) by use of solvents and additives were carried out. Subsequent mixing of the MWCNT into PDMS was carried out to obtain MWCNT/PDMS electrodes. Various solvents, additives and fabrication parameters were investigated to achieve high DC conductivities. We found that by using a combination of solvent and additives, the electrodes could have DC conductivity over 100 times higher than that of plain MWCNT/PDMS electrodes. The experimental results were also compared with other researchers' results. We believe that these findings will lead to improvement of performances of the devices utilizing flexible electrodes.

10163-51, Session 8B

Fabrication and characterizations of a micropump system utilizing ionic polymer-metal composite with inner petal-shaped architecture

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As a critical research area, micropump has extensively emerged for many electronics and biological applications. The diaphragm, a key component of micropump, plays an important role in pumping-system. IPMC is a promising material candidate for micropump diaphragm since it can be operated with low input voltages and can produce a large stroke by appropriate structural design. In this paper, we introduce a kind of petal-IPMC diaphragm obtained by mechanical cutting into micropump. In our previous work [1], we confirm that petal-IPMC with 8 petals in inner petal-shaped structure shows an excellent performance than others. So, 8 petals-IPMC was employed in the experiments. We fabricate 8 petals-IPMCs with the dimension of 1.0cm, 1.5cm and 2.5cm in diameter and measure their electromechanical responses under 1-3V DC and AC voltage. After that, we assemble the micropump by a silicone material and the mentioned 8 petals-IPMC above. The experimental characterizations of the micropump were performed. Experimental results show that the new diaphragm design can produce deformation up to 0.7mm in central point with the dimension of 2.5cm in diameter and maintain stable operation over 1h corresponding to a 2V–0.1Hz input signal, while the conventional design can produce only 0.2mm in deformation and the pumping performance decreases rapidly after 8min. The proposed micropump is attractive due to its low operational voltage, lack of leakage problems, simple design, and ease of manufacturing.

10163-52, Session 8B

Optimization study for fabrication of micro-scale stacked dielectric elastomer actuators

Mert Corbaci, Kathleen Lamkin-Kennard, Wayne W. Walter, Rochester Institute of Technology (United States)

Dielectric elastomer actuators (DEAs) are promising devices with a wide range of possible applications in soft robotics, aerospace, biomedicine and bioengineering. Many improvements have been introduced in the last two decades to enhance the performance of DEAs and to reduce the high voltage requirements to make them more suitable for real life applications. However, most of these improvements have been designed and implemented for macro-scale devices, since there are still some obstacles that need to be overcome with microfabrication of DEAs. Fabrication of micro-scale DEAs could benefit many fields including micro-robots, micro-optical systems besides reducing the driving voltage from kV scale to possibly sub-100V range.

In an earlier study, proof of concept fabrication methods for PDMS-based fiber-like micro-sized stacked dielectric elastomer actuators were introduced. This study tried to optimize the fabrication process by investigating the effect of different fabrication approaches and different design geometries on the performance of micro-sized DEAs. Micro-sized DEAs with varying electrode/dielectric thickness ratios, active surface areas, and actuator lengths were fabricated. Actuation ratios, as well as mechanical strength and stiffness, were investigated for each design and compared.

10163-53, Session 8B

Fabrication of ultra-thin IPMC actuator for flapping motion of butterfly

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As one of electro-active polymers (EAPs), Ionic Polymer Metal Composite (IPMC) has many advantages including bending actuation, low weight, low power consumption and flexibility. These advantages can meet the potential requirements of flapping-wing motion. In this paper, we design and demonstrate an IPMC actuated flapping wing for mimicking flapping motion of a butterfly. Unlike other insects, such as dragonfly, housefly, mosquito etc. with high frequency of vibration (>30Hz on flying), the flapping times of butterfly wing is less than ten times. That's to say, the frequency of butterfly wing is lower than 10Hz. So it is feasible that utilizing IPMC actuator with excellent advantage of low frequency response to imitate the flapping motion of butterfly. Firstly, to improve the low frequency response of IPMC actuator, we fabricate the ultra-thin IPMC actuator with the thickness less than 100μm and Au electroplating was employed in the preparation process. For comparison, three samples with the thickness of 30μm, 60μm and 90μm were separately fabricated. Secondly, the unique structure of flapping wing was designed and obtained by mechanical cutting. We measured the basic deformation and lift force of the flapping wing. When the butterfly is on flying, the flapping is dominating. So, in this paper, we only consider the flapping motion and neglect the impact of twist motion temporarily. Experimental results demonstrated that ultra-thin IPMC actuator has the great potential for use as a flapping wing of butterfly.

10163-54, Session 8B

Microfabricated PEDOT trilayer actuators: synthesis, characterization, and modeling

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Conducting polymer actuators have long been of interest as an alternative to piezoelectric and electrostatic actuators due to their large strains and low operating voltages. Recently, poly (3,4- ethylenedioxythiophene) (PEDOT) – based ionic actuators have been shown to overcome many of the initial obstacles to widespread application in micro-fabricated devices by demonstrating stable operation in air and at high frequencies, along with microfabrication compatible processing using a layer by layer method that does not require any handling. However, there is still a need for characterization, prediction, and control of the actuator behavior. This paper describes the fabrication and characterization of thin trilayers composed of a 5 um thick solid polymer electrolyte (SPE) sandwiched between two 8 um thick PEDOT-containing layers. Beam properties including capacitance, elastic moduli of the layers, and the extent of charge driven strain, are applied to predict curvature, frequency response and force generation. The actuator is represented by an electrical circuit, a mechanical system described via dynamic beam theory, and a strain-to-charge ratio for the electro-mechanical coupling matrix, which together predict the actuator curvature and the resonant response. The success of this physical model promises to enable design and control of micro-fabricated devices.

10163-55, Session 9A

Reliable, robust, electrically powered soft actuators that self-heal from mechanical and electrical damage *(Invited Paper)*

Christoph Keplinger, Univ. of Colorado Boulder (United States)

Soft robots are moving the field of robotics to new areas of application. Currently, soft robots are predominantly relying on pneumatic or fluidic actuators, which limit speed and efficiency. Electrically powered muscle-like actuators, such as dielectric elastomer actuators (DEAs) offer high performance actuation but they come with their own challenges. Being driven by high electric fields, DEAs are prone to failure by dielectric breakdown and electrical ageing. More importantly, DEAs are hard to scale up to deliver high forces, as large areas of dielectric are required (e.g. in stack actuators), which are much more likely to experience premature electrical failure, following the Weibull distribution for dielectric breakdown.

Here a series of advances is presented, that promise to overcome important limitations of electrically powered soft actuators. The presented work introduces I) a highly stretchable self-healing elastomer, that autonomously heals from severe mechanical damage, II) a transparent, self-healing, ionically conductive elastomer that can be used to electrically activate soft electrostatic actuators, III) a new class of versatile, reliable, self-healing muscle-like soft actuators, that use an electro-hydraulic mechanism to combine the strength of fluidic and electrostatic actuators, and IV) a new type of soft electrostatic actuator that linearly contracts upon activation with voltage.

10163-56, Session 9A

Entirely soft dielectric elastomer robots

E.-F. Markus Henke, Auckland Bioengineering Institute, The Univ. of Auckland (New Zealand) and Institut für Festkörperelektronik, TU Dresden (Germany); Katherine E. Wilson, Iain A. Anderson, Auckland Bioengineering Institute, The Univ. of Auckland (New Zealand)

Multifunctional Dielectric Elastomer (DE) devices are well established as actuators, sensors and energy harvesters. Since the invention of the Dielectric Elastomer Switch (DES), a piezoresistive electrode that can directly switch charge on and off, it became possible to expand the wide functionality of dielectric elastomer structures even more. We show the application of fully soft DE subcomponents in biomimetic robotic structures.

It is now possible to couple arrays of actuator/switch units together so that they switch charge between themselves on and off. One can then build DE devices that operate as self-controlled oscillators. With an oscillator one can produce a periodic signal that controls a soft DE robot. Now one has a DE device with its own DE nervous system.

We are fabricating our DES using a special electrode mixture, and imprinting technology at an exact pre-strain. We have demonstrated six orders of magnitude change in conductivity within the DES on a 50% strain. The control signal can either be a mechanical deformation from another DE or an electrical input to a connected dielectric elastomer actuator. We have demonstrated a variety of fully soft multifunctional subcomponents that enable the design of autonomous soft robots without conventional electronics. The combination of digital logic structures for basic signal processing, data storage in dielectric elastomer flip-flops and digital and analogue clocks, with adjustable frequencies, made of dielectric elastomer oscillators (DEOs), puts us in the position to design fully soft, self-controlled and electronics-free robotic structures.

We will present a basic theory on active the dielectric elastomer components and show the most recent robotic demonstrators in action.

10163-57, Session 9A

Fluid electrodes for submersible robotics based on dielectric elastomer actuators

Caleb Christianson, Nathaniel Goldberg, Shengqiang Cai, Michael T. Tolley, Univ. of California, San Diego (United States)

Dielectric elastomer transducers (DETs) have gathered recent interest as actuators for soft robotics due to their low cost, light weight, large strain, low power consumption, and high energy density. However, developing reliable, compliant electrodes for DETs remains an ongoing challenge due to fabrication issues, uniformity problems, and mechanical stiffening of the actuators due to the incorporation of conductive materials with large Young's Moduli. In this work, we present a method for preparing, patterning, and utilizing fluidic electrodes with a simple, inexpensive saline solution serving as the conducting fluid. Further, when we submerse the DETs in a bath containing a conductive fluid connected to ground, the bath serves as a second electrode, obviating the need for the electrode pairs required of most DETs. When we apply a positive potential to the conductive fluid in the actuator with respect to ground, the electric field across the dielectric membrane causes charge carriers in the solution to apply an electrostatic force on the membrane, which compresses the membrane and causes the actuator to expand. We have used this process to develop a submersible robot that is able to swim through a tank of saltwater. Since saltwater serves as the working fluid, we overcome buoyancy issues that may be a challenge for pneumatically actuated soft robots. This research opens the door to low-power underwater robots towards search and rescue and environmental monitoring applications.

10163-58, Session 9A

Actuating materials and fabrication strategies for soft robotics and wearable robotics

Geoffrey M. Spinks, Univ. of Wollongong (Australia)

Soft robotic and wearable robotic devices seek to exploit polymer based artificial muscles and sensor materials to generate biomimetic movements and forces. A challenge is to integrate the active materials into a complex, three-dimensional device with integrated electronics, power supplies and support structures. Both 3D printing and textiles technologies offer attractive fabrication strategies, but require suitable functional materials. 3D printing of actuating hydrogels has been developed to produce simple devices, such as a prototype valve. Tough hydrogels based on interpenetrating networks of ionically crosslinked alginate and covalently crosslinked polyacrylamide and poly(N-isopropylacrylamide) have been developed in a form suitable for extrusion printing with UV curing. Combined with UV-curable and extrudable rigid acrylated urethanes, the tough hydrogels can be 3D printed into composite materials or complex shapes with multiple different materials. An actuating valve was printed that operated thermally to open or close the flow path using 6 parallel hydrogel actuators. Textile processing methods such as knitting and weaving can be used to generate assemblies of actuating fibres. Low cost and high performance coiled fibres made from oriented polymers have been used for developing actuating textiles. Similarly, braiding methods have been developed to fabricate new forms of McKibben muscles that operate without any external apparatus, such as pumps, compressors or piping.

10163-59, Session 9A

A soft flying robot driven by a dielectric elastomer actuator

Yingxi Wang, National Univ. of Singapore (Singapore); Hui Zhang, Southeast Univ. (China); Hareesh Godaba, Boo Cheong Khoo, Jian Zhu, National Univ. of Singapore (Singapore)

Modern unmanned aerial vehicles are gaining promising success because of their versatility, flexibility, and minimized risk of operations. Most of them are normally designed and constructed based on hard components. For example, the body of the vehicle is generally made of aluminum or carbon fibers, and electric motors are adopted as the main actuators. These hard materials are able to offer reasonable balance of structural strength and weight. However, they exhibit apparent limitations. For instance, such robots are fragile in even small clash with surrounding objects. In addition, their noise is quite high due to spinning of rotors or propellers.

Here we aim to develop a soft flying robot using soft actuators. Due to its soft body, the robot can work effectively in unstructured environment. The robot may also exhibit interesting attributes, including low weight, low noise, and low power consumption. This robot mainly consists of a dielectric elastomer balloon made of two layers of elastomers. One is VHB (3M), and the other is natural rubber. The balloon is filled with helium, which can make the robot nearly neutral. When voltage is applied to either of the two dielectric elastomers, the balloon expands. So that the buoyance can be larger than the robot's weight, and the robot can move up. In this seminar, we will show how to harness the dielectric breakdown of natural rubber to achieve giant deformation of this soft robot. Based on this method, the robot can move up effectively in air.

10163-60, Session 9B

Artificial muscles for electrical energy harvesting *(Invited Paper)*

Seon Jeong Kim, Shi Hyeong Kim, Hanyang Univ. (Korea, Republic of); Ray H. Baughman, The Univ. of Texas at Dallas (United States)

The situation exists despite pioneering advances made over the last fifty years on developing energy harvesters based on thermoelectrics, pyroelectrics, ferroelectrics, ferromagnets, and shape memory metals. Little of thermal energy is harvested as electrical energy because present technologies are too expensive. Here we harvest thermal energy as electrical energy by using the newly discovered thermally powered torsional and tensile actuation of artificial muscles made from inexpensive polymer fiber. To get an electrical energy from artificial muscle, we use waste thermal energy to effect large stroke torsional or tensile actuation of an inexpensive polymer artificial muscle. Two embodiments of concept are explored: Firstly, torsional actuation of an artificial muscle directly drives rotation of an attached magnet positioned within a generator. Secondly, tensile actuation of an artificial muscle rotates the shaft of a commercial electric motor, which is run in reverse to generate electricity. From the strength and modulus of polymer fibers, we are doing terrible things to the monofilament fibers by inserting such large twist that the polymer chains form helices and then further inserting so much twist that these helices form coils. For the purpose of making thermally powered artificial muscles, this twist insertion to produce coiling has wonderful benefits – enabling tensile contractions of over 50%, and 27 kW/kg of average mechanical power during muscle contraction. Powerful torsional actuation drives tensile actuation, and we show that both tensile and torsional polymer muscle actuation can be usefully deployed to convert thermal energy to electrical energy.

10163-61, Session 9B

Adaptive gripper using multi-segmented dielectric elastomer with electroadhesion

Jang Ho Park, Siara Hunt, Athul Radhakrishnan, Daewon Kim, Embry-Riddle Aeronautical Univ. (United States)

People use their hands to pick up objects of different shapes. In modern robotics, researchers have developed smart actuators and different types of controllers to mimic the movements of human hands. Despite continued improvements, most robotic hands have been designed for a single purpose and lack versatility. This research focuses on developing a novel method to create an adaptive gripper using dielectric elastomers actuators (DEA), which enable users to pick up objects that are fragile, deformable, and of different shapes. A series of DEA are stacked in small groups and placed in different segments to ensure the greatest optimal range of motions. The primary objective of this research is to mimic the movements of human fingers and joints. Theoretical work includes the study of human hand anatomy in order to adapt its operating mechanism to the DEA. Different types of elastomers are investigated in order to study their material properties. In addition, different geometries of stack orientation are studied to determine the best setup that gives the DEA a wider range of motion. The relationship between the gripping force and the applied voltage for different stack orientations is studied. Work is being conducted to optimize this parameter and increase the gripping force for the same applied voltage. A numerical approach is used to validate the optimal range of motion using commercial software. Increasing gripping force through electroadhesion on the gripper tips is also investigated to supply more gripping force on to different shaped objects.

10163-62, Session 9B

Impedance control for electromechanical transducers based on dielectric elastomers

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Various transducer designs for actuators based on dielectric elastomers have been investigated in the recent years. Minimum energy structures and membrane actuators with supporting structures for example are used to primarily increase the achievable deformation of the overall device, while the generated forces and thus the performed work are comparable small. In contrast, DE multilayer transducers like roll- or stack-transducers combine considerable deformations and forces, and thus, are well suited e.g. for applications in the automation technology or soft robotics. Especially, DE stack-transducers enable high force densities since they almost only consist of active material without passive supporting structure. In addition to an appropriate transducer design, efficient and space-saving high-voltage driving electronics are required for the successful realization of various applications.

Hence, within this contribution a transducer system comprising a DE stack-transducer and a bidirectional flyback-converter as power supply is considered. Based on an analytical model of this system an impedance controller is designed commonly used for example in robotic and haptic feedback applications. The control takes into account the unique, nonlinear characteristics of the stack-transducer and the driving power converter. Furthermore, a measurement of the transducer force is not required to enable the closed-loop control operation. Instead, the force is estimated based on the measured terminal voltage of the DE transducer and its deformation.

Finally, the impedance control is experimentally validated with different scenarios for exemplary applications using a prototypic bidirectional flyback-converter and automatically manufactured DE stack-transducer.

10163-63, Session 9B

Design and motion control of bioinspired humanoid robot head: from servo motors toward artificial muscles

Yara Almubarak, Mohsen Jafarzadeh, Yonas Tadesse, The Univ. of Texas at Dallas (United States)

The potential applications of humanoid robots in social environments motivate researchers to design, model, and control biomimetic humanoid robots. Generally, people are more interested to interact with humanoid robots that have similar attributes and motions to humans. The robot's head is one of most important part of any social robot. Currently, most humanoid heads use electrical motors, pneumatic actuators and shape memory alloy (SMA) actuators. Electrical and pneumatic actuators take most of the space and would generally cause un-smooth motion. SMAs are expensive to deploy them in humanoid robots. Recently, in many robotic projects, Twisted and Coiled Polymer (TCP) artificial muscles are used as linear actuators which only take up a little space compared to the motors. In this paper, we will explain the designing process and motion control of robotic heads in detail. One head utilize servomotors and the other head uses artificial muscles for its actuation. The head motions have been controlled by a cost efficient microcontroller based board. A complete comparison between the two head motions will be presented.

10163-64, Session 9B

Integration of flexible high-voltage thin-film transistors to drive a matrix of dielectric elastomer actuators

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We designed, fabricated, and tested a matrix of 16 thin films transistors (TFTs) that control an array of 16 dielectric elastomer actuators (DEAs) in a flexible haptic display. Each flexible TFTs switches the 1 kV voltage on a DEA using only a 30 V signal on the gate. With our architecture, we can rapidly switch DEAs using the low voltage gate signal. Our approach enables complex arrays of DEAs without a HV switching matrix, using only a single common HV power supply and low-voltage control lines, greatly reducing size and cost. Since the TFTs can be integrated in the flexible frame around the DEA, very high integration is possible.

Although TFTs are very common in consumer electronics, making a compact TFT that can withstand a 1 kV drain-source voltage is far from trivial. Several design and fabrication solutions were implemented, such as a thick Parylene dielectric and an offset gate electrode. The DEAs are 5 mm in diameter, on a 15 μm thick PDMS membrane. The 16 DEAs are printed simultaneously on single membrane using pad printing. The membrane with the actuators is transferred onto the polyimide substrate on which the TFTs are fabricated. The polyimide substrate has a matrix of 4x4 holes, so that the active region of each actuator is suspended and covering the whole hole, thus forming a buckling diaphragm actuator. With a 1 kV bias, the DEAs exhibited an out-of-plane displacement of 300 μm when 0V or 25V was applied on gate of the transistor.

10163-65, Session 10A

Energy analysis of a DEAP-based cylindrical actuator coupled with a radial negative stiffness spring

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The main problem to obtain considerable deformation with dielectric electro-active polymer based technology is the electrical breakdown. A simple solution consists in pre-stretching the elastomer before activating it which cancels the snap-through effect. In this paper, a new design of a monostable spring with a negative stiffness is suggested for a DEAP tubular shape actuator. The particularity of the proposed solution is the radial direction of the displacement with a special load characteristic. In order to determine the performance of the system, the mechanical and electrical behaviour are investigated through analytical models with the assumption that the axial stretch stays constant. A finite element method is used to validate these latter and maximal error lower than 2% is reported. The energy chain conversion is developed in detail which allows studying all the energies transferred from both the electrical input and any pre-stretch solution to the membrane during a cycle of activation. From these models, the negative stiffness spring is compared to the common solution, i.e a constant pressure or a linear positive spring, to pre-stretch a cylindrical EAP. The results show that the linear spring removes always the snap-through behaviour contrary to the constant pressure. Depending on the geometry, the monostable solution cancels also this latter and owns a better energy transfer from the power supply to the elastomer (around 50% against 40% for the linear spring) or a better stroke compared to the linear spring.

10163-66, Session 10A

Development of a soft untethered robot using artificial muscle actuators

Jiawei Cao, Lei Qin, Heow Pueh Lee, Jian Zhu, National Univ. of Singapore (Singapore)

Soft robots attract much interest recently, due to their potential capability to work effectively in unstructured environment. Soft actuators are key components in soft robots. Dielectric elastomer actuators are one class of soft actuators, which can deform in response to voltage. Dielectric elastomer actuators exhibit interesting attributes including large voltage-induced deformation, high energy density, fast response, low weight, and low noise. These attributes make these soft actuators capable of functioning as artificial muscles for soft robots.

It is significant to develop untethered robots, since connecting the cables to external power sources may greatly limit the robots' functionalities, especially autonomous movements. In this paper we develop a soft untethered robot based on dielectric elastomer actuators. This robot mainly consists of a deformable robotic body and two paper-based feet. The robotic body is essentially a dielectric elastomer actuator, which can expand or shrink at voltage on or off. In addition, the two feet can achieve adhesion or detachment based on mechanism of electro-adhesion. In general, the entire robotic system can be controlled by electricity or voltage. By optimizing mechanical design of the robot (say, the size and weight of electric circuits), we put all these components (such as batteries, voltage amplifiers, control circuits, etc.) onto the robotic body, and the robot is capable of realizing autonomous movements. Experiments are conducted to study the robot's locomotion. Finite element method is employed to interpret the deformation of dielectric elastomer actuators, and the simulations are qualitatively consistent with the experimental observations.

10163-67, Session 10A

Electrically tunable window based on unfolding of wrinkled ZnO/Ag thin film

Milan Shrestha, Rosmin E. Mohan, Anansa S. Ahmed, Anand K. Asundi, Gih-Keong Lau, Nanyang Technological Univ. (Singapore)

This paper presents an electrically tunable window based on unfolding of wrinkled ZnO/Ag thin film. A zinc oxide (ZnO) thin film is transparent, brittle, and electrically insulating. Its laminated with silver (Ag) thin film and wrinkling makes a compliant electrode capable of tuning transparency. A laminate composite electrode of 30nm thick ZnO/10nm thick Ag, which were coated on a pre-stretched polyacrylate elastomer substrate (3M VHB 4910), has 22.5kΩ/◊ surface resistance and 62.4% in-line transmittance at its flat state. It forms micro-wrinkles under 10% mechanical radial compression to have transmittance reduced down to 1.8%. Despite this large compression, the laminate of Ag/ZnO does not crack due to their nanometric thickness. An electrically tunable window device of is made of a pre-stretched dielectric elastomer membrane sandwiched by a pair of such wrinkled Ag/ZnO compliant electrodes of 2 cm diameter and a 0% in-line transmittance. A 6.5kV (50MV/m) activation of this device produces a 10% radial expansion to unfold the wrinkled electrodes and restore the in-line transmittance to 45%. The device was tested for cyclic electrical activation for 3800 cycles at 0.033Hz. They consumed 0.18watt at each activation cycle. These properties suggest that this device can make a low-cost high-performance smart window. In conclusion, this low-cost tunable window device has an electrical tuning range of transparency comparable to the existing smart windows based on electrochromic glasses and liquid crystal devices.

10163-68, Session 10A

Dielectric elastomer grippers using tensioned arch flexures

Kim-Rui Heng, Anansa S. Ahmed, Gih-Keong Lau, Nanyang Technological Univ. (Singapore)

Soft-grippers based Dielectric Elastomer Actuator (DEA) are usually too flimsy to perform the task of pick and place. They carry only low payload and their range of applications is limited. So far, Dielectric minimal energy structure (DEMES) actuators produce a maximum gripping force of not more than 12 mN and a maximum tip angle change of 63.0°. In this study, we use a new tensioned arch flexure as a soft gripper to improve the clamping and holding forces. The tensioned arch flexure has stiff PVC spines to support Polyimide (PI) arches. The PI arches raise the bending moment arm of the gripper off the basal plane. This makes longitudinal bending of the stiff PVC spines possible by pre-stretched dielectric elastomer membrane. This novel design results in a high stiffness gripper with 10 fold increase in the voltage-induced gripping force (168.7 mN) as well as an increase in the voltage-induced tip rotation (86.6°) as compared to previous grippers. The gripper is capable of lifting various objects including a weighted Styrofoam ball (65.6 kg), a mandarin orange (47 g) and a raw egg yolk (10 g), which demonstrates its versatility in handling either rigid or soft compliant objects without damage.

10163-69, Session 10B

From elastomeric flight muscles to tunable window *(Invited Paper)*

Gih-Keong Lau, Yao-Wei Chin, Kim-Rui Heng, Anansa S. Ahmed, Milan Shrestha, Nanyang Technological Univ. (Singapore)

Dielectric elastomer actuators were thought to be promising to make artificial flight muscles for driving of man-made flapping-wing micro-aircraft (ornithopter). Dielectric elastomer actuator can produce a large voltage-induced actuation do while its elastic energy storage is good like natural muscles for recovering the wing kinematic energy. We have come out a number of insect-inspired compliant thoracic mechanism and stacked dielectric elastomer actuator to prove the concept. Some issues in the integration of stacked dielectric elastomer actuator have be resolved, namely 1) the prevention of premature dielectric breakdown of multi-layered dielectric and 2) self-clearable metallic thin-film compliant electrodes. However, the structure, which is needed to keep the large pre-stretch of DEA, adds substantial passive weight to reduce the system's effective energy density and the actuation speed. This motivates the development of lightweight tensioned arch flexure to produce a large voltage-induced unbending, sub-Newton high force, and large resonant amplitude at 8Hz. Though the developed DEAs have yet powered the ornithopter's take-off, the artificial-muscles research has spun off an unexpected success, i.e. the dielectric-elastomer window device using variable-transparent compliant electrodes. Such tunable window device is capable of full transparency tuning far better than the commercial smart window.

10163-70, Session 10B

Exploring dielectric elastomers as actuators for hand tremor suppression

Christopher R. Kelley, Jeffrey L. Kauffman, Univ. of Central Florida (United States)

Individuals who suffer from parkinsonian hand tremor have difficulty performing simple day-to-day tasks, such as eating, writing, and grasping items. Typical treatment includes drug therapy, physical therapy, and surgical intervention. Since any surgery has the risk for complications, an alternative is desired for cases where drugs and physical therapy are ineffective. Mechanical suppression of parkinsonian tremor is being actively researched as an alternative to surgery. Researchers have proposed active tremor suppression systems that use DC motors, MR dampers, and pneumatic cylinders.

This work explores the viability of dielectric elastomers as the actuators in a tremor suppression control system. Dielectric elastomers have many properties similar to human muscle, making them a natural fit for integration into the human biomechanical system. By essentially matching the impedance of the wrist, dielectric elastomers may provide greater user comfort while offering enough control authority to suppress tremor. First, this study evaluates the open-loop dynamics of the integrated dielectric elastomer-wrist system to determine the effect of the actuator on voluntary motion. Then this investigation uses the open-loop and voltage frequency responses to determine actuator parameters that produce the necessary control authority in the tremor frequency range without significantly affecting voluntary motion. Finally, this paper works towards a control law based on research that indicates parkinsonian tremor is the result of an increased feedback delay in the human neurosensory system. Altogether, this work seeks to advance mechanical suppression of tremor through the use of a more human-compatible actuator along with a control law that uses information about the dynamics of parkinsonian tremor.

10163-71, Session 10B

Hydrogels for engineering: normalization of swelling due to arbitrary stimulus

Adrian Ehrenhofer, Thomas Wallmersperger, TU Dresden (Germany)

Hydrogels swelling due to an external stimulus mostly undergo isotropic volume change. This behavior can be found for stimuli like the change in temperature, pH-value, ion concentrations and light intensity.

A multitude of different multisensitive hydrogels are present in literature. The utilization of mass- or volume swelling ratio, masses, volumes or diameters for their characterization makes it hard to compare and choose hydrogels for a specific application.

Since the respective swelling-stimulus curves have roughly the same shape, they can be normalized to make them universally understandable.

We propose a normalization based on the reference point which allows the definition of a stimulus ratio and logarithmic (Hencky-) strain.

The sensitivity of actuation which makes a material more suitable for precise actuation or for a sensor application can be derived from this normalized behavior.

Data taken from literature and from experimental measurements performed at TU Dresden for differently sensitive hydrogels are presented and the procedure of normalization is described.

By using the Temperature Expansion Model - an analogy model for isotropic thermal expansion - it is easy to implement swelling due to arbitrary stimulus in commercial Finite Element software.

The normalized swelling allows engineers and designers to use smart materials in their constructions even without distinct knowledge about the chemical background.

Together with the community, we hope to establish an industrial standard for hydrogels. This might lead to more intensive use of hydrogels in industry.

10163-72, Session 11A

Bottlebrush elastomers: a promising molecular engineering route to tunable, prestrain-free dielectric elastomers *(Invited Paper)*

Mohammad Vatankhah-Varnosfaderani, William F. M.

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Electroactive polymers (EAPs) refer to a broad range of relatively soft materials that change size and/or shape upon application of an electrical stimulus. Of these, dielectric elastomers (DEs) generated from either chemically- or physically-crosslinked polymer networks afford the highest levels of electroactuation strain, thereby making this class of EAPs the leading technology for artificial-muscle applications. While mechanically prestraining elastic networks remarkably enhances DEs electroactuation, external prestrain protocols severely limit both actuator performance and device implementation due to gradual DE stress relaxation and the presence of a cumbersome load frame. These drawbacks have persisted with surprisingly minimal advances in the actuation of single-component elastomers since the dawn of the "pre-strain era" introduced by Pelrine et al. (Science, 2000). In this work, we present a bottom-up, molecular-based strategy for the design of prestrain-free (freestanding) DEs derived from covalently-crosslinked bottlebrush polymers. This architecture, wherein design factors such as crosslink density, graft density and graft length can all be independently controlled, yields inherently strained polymer networks that can be readily adapted to a variety of chemistries. To validate the use of these molecularly-tunable materials as DEs, we have synthesized a series of bottlebrush silicone elastomers in as-cast shapes. Examination of these materials reveals that they undergo giant electroactuation strains (>300%) at relatively low fields (<10 V/m), thereby outperforming all commercial DEs to date and opening new opportunities in responsive soft-material technologies (e.g., robotics). The molecular design approach to controlling (electro)mechanical developed here is independent of chemistry and permits access to an unprecedented range of actuation properties from elastomeric materials with traditionally modest electroactuation performance (e.g., polydimethylsiloxane, PDMS). Experimental results obtained here compare favorably with theoretical predictions and demonstrate that the unique behavior of these materials is a direct consequence of the molecular architecture.

10163-73, Session 11A

Deformation behavior of carbon-fiber reinforced shape-memory-polymer composites used for deployable structures

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Shape memory polymers (SMPs) are a new type of smart material, they perform large reversible deformation with a certain external stimulus (e.g., heat and electricity). The properties (e.g., stiffness, strength and other mechanically static or quasi-static load-bearing capacity) are primarily considered for conventional resin-based composite materials which are mainly used for structural materials. By contrast, the mechanical actuating performance with finite deformation is considered for the shape memory polymers and their composites which can be used for both structural materials and functional materials. For shape memory polymers and their composites, the performance of active deformation is expected to further promote the development in smart active deformation structures, such as deployable space structures and morphing wing aircraft. The shape memory polymer composites (SMPCs) are also one type of High Strain Composite (HSC).

The space deployable structures based on carbon fiber reinforced shape memory polymer composites (SMPCs) show great prospects. Considering the problems that SMPCs are difficult to meet the practical applications in space deployable structures in the recent ten years, this paper aims to research the mechanics of deformation, actuation and failure of SMPCs. In the overall view of the shape memory polymer material's nonlinearity (nonlinearity and stress softening in the process of pre-deformation and recovery, relaxation in storage process, irreversible deformation), by the multiple verifications among theory, finite element and experiments, one obtains the deformation and actuation mechanism for the process of "pre-deformation, energy storage and actuation" and its non-fracture constraint domain. Then, the parameters of SMPCs will be optimized. Theoretical analysis is realized by the strain energy function, additionally considering the interaction strain energy between the fiber and the matrix. For the common resin-based or soft-material-based composites under pure bending deformation, we expect to uniformly explain the whole process of buckling occurrence, evolution and finally failure, especially for the early evolution characteristics of fiber microbuckling inside the microstructures. The research results are meaningful for the practical applications for SMPC deployable structures in space.

Considering the deformation mechanisms of SMPCs, the local post-microbuckling is required for the unidirectional fiber reinforced composite materials, at the conditions of its large geometrical deflection. The cross section of SMPC is divided into three areas: non-buckling stretching area, non-buckling compressive area, and buckling compressive area. Three variables are considered: critical buckling position, and neutral plane, the fiber buckling half-wavelength. Considering the condition of the small strain and large displacement, the strain energy expression of the SMP/fiber system was derived, which contains two types, e.g., strain energy of SMP and fiber. According to the minimum energy principle, the expression for all key parameters were derived, including the critical buckling curvature, neutral plane position, the buckling half-wavelength, fiber buckling amplitude, and strain.

10163-74, Session 11A

A novel sheet actuator using plasticized PVC gel and flexible electrodes

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The plasticized polyvinyl chloride (PVC) gel exhibits a fast response in air, large deformation, and low power consumption under an electrical field, so it shows great potential for use as a new type of soft actuator. In our previous study, we have developed a multilayered expansion and contraction-type actuator using PVC gel and stainless mesh electrodes, with a contraction strain of about 10-20%, output stress of about 0.1Mpa and a response rate of 9Hz under a low driven field of about 2 V/μm. In this study, to develop an actuator with higher performance and flexibility, we proposed a novel sheet actuator using PVC gel and flexible electrodes. And we conducted some preliminary experiments to investigate the basic characteristics of the actuators. We found that the PVC gel sheet actuator can be driven under a low DC field of about 0.5 V/μm, and obtained an expansion ratio of 76% under a DC field of about 15 V/μm. Also, we discussed the relations between different parameters and characteristics of the actuators. Besides, we conducted a comparison experiment between the proposed PVC gel sheet actuators and the traditional dielectric elastomer actuators, founding that, the PVC gel sheet actuator had a positive potential to be driven at a lower voltage to get a bigger deformation and a faster response than those of the traditional dielectric elastomer actuator. And we discussed the difference between the two types of actuators with a theoretical model, finding a good agreement with the experimental results.

10163-75, Session 11A

Film stretching influence on lifetime of DEAP system

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Dielectric electroactive polymers (DEAP) are known to have promising applications in actuators (DEA) and energy harvesting devices (DEG).

However, they suffer of high failure rates during operation that prevents their use in large scale applications. This is mainly due to dielectric breakdown. To prevent this failure mechanism, film pre-stretching is a widely adopted solution to improve dielectric strength of the whole DEAP system. However, to date, long term reliability of this solution has not been investigated.

In this work it is explored how the dielectric elastomer lifetime is affected by the amount of pre-stretch used. The dielectric loss of soft polydimethylsiloxane (PDMS) films is studied for different stretch ratios by measuring tan? value at frequency range from 1 mHz to 10 kHz. Additionally, time-to-breakdown was measured at DC electric stress for different stretch ratios. For comparison, under the same test conditions, the same measures were repeated on non-pre-stretched samples.

This study suggests that no additional dielectric losses are caused by film stretching up to 80% of original dimensions. Furthermore it is shown that the dielectric loss of this material can be influenced by the presence of dust in the experiment's environment.The results of the breakdown tests show that the breakdown strength of this material is dependent to the rate of change of the applied voltage.

10163-76, Session 11A

Development of novel textile and yarn actuators using plasticized PVC gel

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Soft actuators based on polymers are expected to be used for power sources to drive wearable robots which required in a wide range of fields such as medical, care and welfare, because they are light weight, flexible and quiet. Plasticized PVC gel which has a large deformation by applying a voltage and high driving stability in the atmosphere is considered as a suitable candidate material for development of soft actuator. Then, we proposed two kinds of novel flexible actuators constructed like yarn and textile by using plasticized PVC gel in order to develop soft actuator to realize a higher flexibility and low-voltage driving. In this study, we prepared prototypes of these actuators and clarify their characteristic. In addition, we considered the deformation model from its characteristics and geometric calculation. When a voltage was applied to their actuators, textile type actuator contracted, while the twisted yarn type actuator expanded. The deformation behavior of the proposed actuators could be found at a low voltage of 200V, the contraction strain of the textile actuator was about 10 %, the expanding ratio of the yarn actuator was 0.2 %. This results indicated that the structure of the proposed actuators can be effective to low voltage driving. From this results, we proposed geometric models of the deformation behavior and compared with the experimental results. The calculation results from the proposed model were in roughly agreement with the experimental values. It indicated that deformation behavior of these actuators was able to estimate from simple geometric models.

10163-77, Session 11B

Electrical breakdown phenomena of dielectric elastomers *(Invited Paper)*

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Silicone elastomers have been heavily investigated as candidates for dielectric elastomers and are as such almost ideal candidates with their inherent softness and compliance but they suffer from low dielectric permittivity. This shortcoming has been sought optimized by many means during recent years. However, optimization with respect to the dielectric permittivity solely may lead to other problematic phenomena such as premature electrical breakdown. In this work, we investigate the electrical breakdown phenomena of various types of permittivity-enhanced silicone elastomers. Various types of silicone polymers are investigated and different types of breakdown are discussed. Furthermore the use of voltage stabilizers in silicone-based dielectric elastomers is investigated and discussed.

10163-78, Session 11B

Viscoelastic performance of dielectric elastomer subject to different voltage stimulation

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Dielectric elastomer (DE) is capable of giant deformation subject to an electric field, and demonstrates significant advantages in the potentially application of soft machines with muscle-like characteristics. Due to an inherent property of all macromolecular materials, DE exhibits strong viscoelastic properties. Viscoelasticity could cause a time-dependent deformation and lower the response speed and energy conversion efficiency of DE based actuators, thus strongly affect its electromechanical performance and applications. Combining with the rheological model of viscoelastic relaxation, the viscoelastic performance of a VHB membrane in a circular actuator configuration undergoing separately constant, ramping and sinusoidal voltages are analyzed both theoretically and experimentally. The theoretical results indicated that DE could attain a big deformation under a small constant voltage with a longer time or under a big voltage with a shorter time. The model also showed that a higher critical stretch could be achieved by applying ramping voltage with a lower rate and the stretch magnitude under sinusoidal voltage is much larger at a relatively low frequency. Finally, experiments were designed to validate the simulation and show well consistent with the simulation results.

10163-79, Session 11B

Continuum vibration analysis of dielectric elastomer membranes

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Dielectric Elastomer (DE) transducers are well known for the possibility of responding to an applied voltage with relatively large actuation strains, often larger than 100%, and for their relatively high actuation bandwidth (of several kHz). Typical applications of DE Actuators (DEA) include pumps or valves, in which the membrane is usually operated at relatively low frequencies (< 100 Hz). On the other hand, the large bandwidth opens up the possibility of using DEA's in high-frequency applications as well, including loudspeakers, system which generate motion in a fluid, or sensors capable of measuring deformation profile of a surface. Motivated by the potentialities of DE in high-frequency applications, the aim of this work is the investigation of the continuous vibrations observed in circular DE membranes.

The system used to study the vibrations consists of a circular DE membrane pre-loaded with a linear spring. Vibration are generated by applying high-voltage, high-frequency voltage signals to the DE membrane. A 3D laser vibrometer, capable of detecting the velocity of a moving object via Doppler effect, is used to reconstruct the three-dimensional motion of several fixed points on the membrane, allowing to visualize and acquire the oscillations of the surface of the membrane. Experimental investigations are performed in order to study the effects of geometry and pre-stress on the membrane motion, in terms of frequency spectrum and resulting vibration modes.

10163-80, Session 11B

Breakdown detection system for dielectric elastomer actuators

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Electrical breakdown of dielectric elastomer actuators (DEAs) is an issue that has to be carefully addressed when designing systems based on this novel technology. Indeed, in some systems electrical breakdown might have serious consequences, not only in terms of interruption of the desired function but also in terms of safety of the overall system (e.g. overheating and even burning). The risk of electrical breakdown often cannot be completely avoided by simply reducing the driving voltages, either because completely safe voltages might not generate sufficient actuation or because internal or external factors might change some properties of the actuator while in operation (for example the aging or fatigue of the material, or an externally imposed deformations decreasing the distance between the compliant electrodes). So, there is the clear need for reliable, simple and cost-effective detection systems able to acknowledge the occurrence of a breakdown event, making DEA-based devices able to monitor their status and become safer and "self-aware".

Here we report a simple solution based on a voltage-divider configuration that detects the voltage drop at the DEA terminals and assesses the occurrence of breakdown via a microcontroller (Beaglebone Black single-board computer) combined with a real-time, ultra-low-latency processing unit (Bela cape - an open-source embedded platform developed at Queen Mary University of London). The system is used to both generate the control signal that drives the actuator and constantly monitor the functionality of the actuator, detecting any breakdown event and discontinuing the supplied voltage accordingly, so as to obtain a safer controlled actuation. This paper presents tests of the detection system in different scenarios in order to assess its reliability.

10163-81, Session 12A

New approach to improve the energy density of hybrid electret-dielectric elastomer generators

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Dielectric elastomers generators (DEGs) represent one of the most promising technologies for harvesting human kinetic energy to power wearable electronic devices. These electrostatic generators are variable capacitors made of a soft dielectric membrane sandwiched between two compliant electrodes. One of the main disadvantages of these structures is the need of an external polarization source to perform the energetic cycle.

In order to overcome these problems, our research group proposed a hybrid electret-DE generator which harvests mechanical energy to generate electricity by charges reorganization between two compliant electrodes of a variable capacitor. The energy density obtained with this autonomous generator was theoretically 1.44mJ*g-1, and experimentally 0.55mJ*g-1.

In the present work, an original approach was employed to further increase the energy density of this hybrid generator. This method consists in raising the voltage of the charges transferred between the two electrodes by exploiting the capacitance variation of the dielectric elastomer membrane. The electret is thus used as polarization source of a classical DEG. The increase in voltage due to the transferred charges can lead to an increase in the electrical energy output, which is a function of the membrane deformation rate. In this paper, the operation principle of the generator will be fully described and the design rules for the realization of the prototype will be presented. The experimental data obtained from the prototype will be compared to the results of numerical simulations. Future challenges of this type of approach will also be discussed.

10163-82, Session 12A

A dielectric elastomer-based tactile display for multiple fingertip interaction with virtual soft bodies

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In this paper we present our new wearable tactile haptic display for rendering soft body sensations to multiple fingertips with electroactive smart elastomers. The system uses our newly developed multi-layered hydrostatically coupled Dielectric Elastomer Actuators, which have been designed to apply a localised tuneable force to a user's fingertip via a soft electrically-deformable interface. The system is comprised of DEA actuators which are fingertip mounted and are driven individually by a wired connection to a control unit. The force applied to the user's fingertip is based on the user's fingertip position which is monitored by an optical three dimensional finger tracking system. This novel tactile display system is conceived to conveying soft body interactions within virtual environments. To demonstrate this, we have created a simulator of avocado ripeness. Participants are asked to discriminate and compare different virtual avocado's that have varying soft body properties using our tactile haptic device. The paper presents preliminary results of ongoing testing, as well as data pertaining to the characterisation of the device in terms of maximum displacement, force and frequency response. The paper also outlines the current limitations of the proposed technology and challenges to be addressed for further developments.

10163-83, Session 12A

Use of a thermoplastic elastomer gel with shape memory behavior as a bimorphic dielectric elastomer

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Shape memory polymers have received a great deal of attention in the recent polymer science literature. New molecular mechanisms and materials that can undergo stimuli responsive conformation changes are regularly introduced, but many of these suffer from an important drawback—there is no intrinsic mechanism to reprogram temporary shapes. In any applications for shape memory devices that require more than a single use, shapes must be reprogrammed. The ability to remotely reprogram a shape for cyclic use would extend the scope of shape memory polymers to applications involving mechanical dynamics and long device lifetimes.

Here, we have used a thermally responsive thermoplastic elastomer gel (TPEG) with shape memory behavior that can be remotely reprogrammed using a combination of AC and DC stimuli. The reprogramming mechanism is accomplished using a dielectric elastomer actuator wherein the dielectric layer changes mechanical states based on temperature. The thermal switching is controlled using a high frequency AC signal to cause heating due to resistive and dielectric losses and the actuation is controlled via high voltage DC, just as with a traditional dielectric elastomer.

The shape memory actuator is a three-layer composite wherein all layers are a TPEG comprised of a triblock copolymer and a midblock selective solvent that is crystalline at room temperature. The top and bottom layers additionally have a carbon nanofiber (CNF) additive to impart electrical conductivity. Electrical resistivity and impedance measurements have been used to characterize electrode performance; resistivity was found to be

~101 Ohm m. Shape memory mechanics show a mechanical strain fixity of >98%, and electromechanical strain fixity of >95% and nearly perfect strain recovery. Additionally, electromechanical behavior matches well with previously published results of a SEBS based TPEG with relatively large actuation strains (>60% area strain).

It has been demonstrated that this shape memory dielectric elastomer can remotely reprogram desired biaxial strain states into a shape memory polymer. The TPEG demonstrates exceptional shape memory behavior with low hysteresis. A simple heat loss model (function of voltage, frequency, and geometry) has been applied to predict melting and crystallization times and the relation of crystallinity to strain fixity.

10163-84, Session 12A

Experimental test of a dynamically tuned wave energy converter based on inflatable dielectric elastomer generators

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Dielectric Elastomer Generators (DEGs) are very promising systems that are able to directly convert oscillating mechanical energy into direct electricity. Their nature and main attributes make them particularly interesting for harvesting energy form ocean waves. In this context, several efforts have been made in the last years to develop effective Wave Energy Converters based on DEG [1-4].

In this contribution, we present a novel Wave Energy Converter (WEC) based on the Oscillating Water Column principle. The device features an inflatable DEG as Power Take Off (PTO) system and collector - i.e. the part of the device that is directly interacting with waves – that possesses a coaxial-ducted shape as described in [5].

Models of the coupled behavior that consider the electro-hyperelastic response of the DEG and the hydrodynamics are presented. It is shown that the dynamic response and the effectiveness of the system can be largely improved through an appropriate dimensioning of the geometry of the device. Specifically, the dynamic response of the system can be designed to match the corresponding harmonic content of water waves achieving an effective conversion of the incoming mechanical energy.

A small/intermediate scale prototype of the system is built and tested in a wave tank facility - i.e. a basin in which artificially controlled waves can be generated - available at Flowave (UK).

Mathematical models are validated against experimental results for monochromatic and panchromatic tests. During the experiments, we obtained peak of estimated power output in the range of 1 W to 4 W with an energy density for the dielectric material of approximately 80-120W/kg.

The achieved results represent a milestone in the study of WEC based on DEG, paving the path toward scaling up of this technology.

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10163-85, Session 12A

Surface texture change on-demand and microfluidic devices based on thickness mode actuation of dielectric elastomer actuators (DEAs)

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The in plane deformations produced by the dielectric elastomer actuators (DEAs) can be used to produce out of plane deformations by what is known as the thickness mode actuation of DEAs. [1,2] The thickness mode actuation is achieved by adhering a soft passive layer to the DEA, and the previous work shows that the out of plane deformation produced depends on factors like thicknesses of the dielectric layer and the passive layer, dielectric constant, and modulus of elasticity of the dielectric and the passive layer. [1,2] This enables a whole area of applications in tactile applications without the need of complex systems and multiple actuators.

But the thickness mode actuation has not been researched enough to understand how the deformations can be improved without altering the material properties, which is always accompanied with increased cost and a trade off with other associated properties. We have shown the effect of dimensions of electrodes in manipulating the out of plane deformation. Making use of this, we have been able to demonstrate multiple patterns on the passive top layer for the on-demand surface texture change application for automotive interiors. We have also been able to demonstrate the microfluidic devices without the need of actually fabricating the channels, which is a cost incurring and sometimes cumbersome process.

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10163-86, Session 12A

Rubbery computing

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Mechanically coupled dielectric elastomer actuators (DEAs) and dielectric elastomer switches (DESs) can form digital logic circuitry made entirely of soft and flexible materials. The expansion in planar area of a DEA exerts force across a DES, which is a soft electrode with strain-dependent resistivity. When compressed, the DES drops steeply in resistance and changes state from non-conducting to conducting. A paired DEA and DES, then, behaves as an inverter: a high voltage (logical value 1 in binary) input to the DEA causes expansion of the membrane, consequently compressing the neighbouring DES, which then conducts to ground so that the output voltage across the switch becomes low (logical value 0). Inversely, a low voltage input to the DEA will not induce actuation and the DES will remain in a state inhibiting charge flow, thus the output voltage across the switch is high. In addition to the inverter, other logical operators may be achieved with different arrangements of DE actuators and switches. We demonstrate combinatorial logic elements, including the fundamental Boolean logic gates, as well as sequential logic elements, including common types of flip-flops. With both data storage and signal processing abilities, the necessary calculating components of a soft computer are available. A noteworthy advantage of a soft computer with mechanosensitive DESs is the potential for responding to environmental strains while locally processing information and generating a reaction, like a muscle reflex. We will discuss the structure and challenges of DE computers and how DE computing networks may be integrated with soft machines and designed for diverse applications.

10163-87, Session 12A

Interactive haptic display based on soft actuator and soft sensor

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This paper demonstrates a new haptic display based on soft actuator and soft sensor, which was reported as “active skin” previously. The device consists of an array rigid coupling actuator and an array tactile sensor which configured sensor located on the top of actuator. The actuator includes a frame with rigid coupling made by silicone and a dielectric elastomer actuator. The movement of the DEA is transferred to touch pad via rigid coupling. Thus, it provides a soft, comport touch feeling and eliminates the danger of applying high voltage to the human skin. The actuator can work at a wide range frequency of 0-150Hz and produce sufficient force of 50mN over the human hand threshold. The tactile sensor can measure the pressure, locate the objects and send the feedback signals to control the actuator. In this work, a 16x24 haptic tactile display is made with high resolution. In addition, the high voltage signal processing also developed to generate variable 0 – 6kV, and can control individual cell by using the dynamic scanning actuation algorithm. Then, it can display any shape such as a circle, a smile/sad face, a star, etc. In the future, we will build the “emotion touch pad” system which can transfer a person’s emotion to another one via internet.

10163-88, Session 12B

Stackable configurations of artificial muscle modules that is continuously-tunable by voltage *(Invited Paper)*

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A dielectric elastomer actuator is capable of producing electrically-induced strains in excess of 100%. Over the past decade, actuation strains ranging from a few percent to more than 1000% (in area strain) has been demonstrated on different geometries. Electromechanical instability has either been suppressed or harnessed to produce strains of very large magnitudes. We present a simple way to produce continuously-tunable strains in excess of 100%. This geometry allows the actuator to expand freely with no constraints under an electric field, giving an unimpeded electrically-induced actuation of about 150%. Such an actuation does not require the attachment of any rigid frames or dead loads in the direction of the actuation, thereby allowing the actuator to be freed to perform mechanical work. We further present modules of actuators that may be easily scaled up in terms of actuation displacement and blocking force. This is integrated in a system that powers an electroactive-polymer-powered arm.

10163-89, Session 12B

Micro-fabrication of a noval linear actuator

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The noval linear actuator is researched with light weight, small volume, low power comsumption, fast response and relatively large displacement output. It can be used for the net surface control of large deployable mesh antennas, the tension precise adjustment of the controlled cable in the tension and tensile truss structure and so on. The structure and the geometry parameters are designed and analysised by finite element method in multi-physics coupling. Meantime, the relationship between input voltage and displacement output is computed, and the strength check is completed according to the stress distribution. Carbon fiber reinforced composite (CFRC), glass fiber reinforced composited (GFRC), and Lead Zirconium Titanate (PZT) materials are used to fabricate the actuator by using laser etching and others MEMS process. The dispalcement output is measured by the laser displacement sensor device with the input voltage range of DC0-180V. The response time is obtained by oscilloscope at the arbitarily voltage in the above range. The nominal force output is measured by the special mechanics setup, which has large displacement sensitivity. Finally, the computed and test resuts are compared and analysised.

I. Introduction

With rapid development of antennas techonology, the actuator plays an important in the antennas structure control system. Such as the net surface control of large deployable mesh antennas1-2, the tension precise adjustment of the controlled cable in the tension and tensile truss structure3-4 and so on, they all need an actuator. Considering the limited payload space volume and the gross weight of the launching load, and the high integration of the antennas structure, the actuator needs to have light weight and small volume characteristics. Additionally, the limited power provision in spaceborne antennas, the adjustment quantity and response time of the control system, they demand the actuator has low power comsumption, fast response and relatively large displacement output. Traditionally, the electromagnetic linear motor has large weight, large power consumption, and large number of electric and control wires. Actuator based on shape memory alloy (SMA) exhibits low response rate, due to the large time needed for temperature cooling. The electric active polymer (EAP) actuator has large volume when the large displacement is needed, and the high input voltage is needed. The actuator based on piezoelectric materials mainly contains piezoelectric piles, piezoelectric motor5-9, and inchworm motor10-12. Piezoelectric piles has large weight, large volume, and tens micrometer displacement output. The piezoelectric motor demands large input power. The output force of the micro-inchorm motor is little (mN), because its work priciple is based on static electricity. Thus, the noval linear actuator is researched with light weight (<1g), small volume (15mmx15mmx15mm), few power comsumption (mW), fast response (ms) and relatively large displacement (hundards micrometer) output.

II. Structure design

The structure of the actuator is designed with double cantilevers, which are fixed in the CFRP plate. The cantilever is a bimorph, a sandwich structure, which is composed of PZT and GFRC plates.The actuator can expand and contract, when different voltage is applied. The direction of the polarization of the plates in one cantilever is oppisited. Using the inverse piezoelectric effect, when the DC voltage is applied to the two outer PZT plates, along the polarization direction, the plates can produce expansion bend. The ends of the cantilevers can yield identical displacement in their outer direction, respectively. When the voltage is applied to the others PZT plates, along the polarization direction, they can produce the contraction bend. The ends of the cantilevers can yield identical displacement in their inner direction, respectively. In fact, alternatively applied the voltage to piezoelectric ceramic plates can yield two times displacement output as a single voltage applied. The circle hole in one end of the beam is used for the tension cable connection. When it is connected to the cable, prestressed, the tension in the cable can be adjusted by this actuator by varing the displacement out of the actuator.

The geometry parameters of the actuator are designed by finite element method by commercial software for multi-physics fields coupling analysis. Considering batch production, integration, and the current fabrication process, the thickness of the piezoelectric ceramic and GFRC plates are desigened as 200μm. When the width is 8mm, the displacement output of the actuator is calculated at different length. From this result, the approximate square relation between the displacement output and the length of cantilever. The displacement output increases with the length increasing. When the length increases to 20mm, the displacement output

reaches to 120?m. The displacement output keeps constant, and it dosen't vary with the width of cantilever.

When the length is 10mm and the input voltage is180V, the relationship between nominal force output and the width of the cantivilever is researched. They are linear. The width ranges from 4mm to 16mm, corresponded to the nominal force output of 0.5-2.5N, and the proportion coefficient is 6.

By the above calculation and analysis, the thickness, width, and length of the PZT plate are designed as 0.2mm, 8mm, and 10mm, respectively. The thickness and width of the GFRC plate are identical to that of piezoelectric ceramic plate. In order to fabricate lead electrode, the length of GFRC plate is designed to be 12mm. The relationship between input voltage and displacement output is analysised. The displacement output is in direct proportional to the input voltage. When the voltage 180v is applied to actuator, the displacement output reaches to 33?m. The maximum stress appears to be 45Mpa, which is less than the yield strength of these materials used. The calculated results only considering the cotraction work mode, when the actuator work in both contraction and expansion mode, the displacement output can reaches to 66?m, and the nominal force 1N may be obtained. When it is used for the tension control of the cable, the tension variation 2N in the cable could be obtained.

III. Experimental

The actuator mainly contains patterned bimorphs and CFRC, and they are all patterned by lasering etching. The CFRC material is used to fabricate the connection plate, because of its large elasticity modulus, electric conductivity, and low density. The composited bimorph with copper and siliver electrode is used to fabricate cantilever. The fabrication process of the actuator contains four steps, as follows: In step (1), the laser cut device with etching width 20?m and etching power 5W was used to pattern the connection plate. In step (2), biomorphs were fabricated into cantivilevers by using the same laser device. In order to avoid the air breakdown of PZT plate, the margin region of the siliver electrode on top of the PZT plate was removed by lasering etching or by the scalpel. In step (3), the connection plate and cantivilevers were glued together by conductive adhesive, which can be cured in low temperature and has high bonding strength, and the glued actuator was cured in 80? for an hour. Too high cure temperature may cause the PZT material depolarization.

IV. Measurement

After bonding the electric leads, the performance of the actuator is measured. The displacement output will be measured by laser displacement sensor, which has high measurement precision 0.2?m. Combined the laser displacement sensor (KEYENCE LK008) and oscilloscope (Tektronix TDS2022C), the response time of the actuator will be tested. The mechanics measurement equipment (PTR-1101) with large stiffness and high diaplacement resolution can be used to evaluate the nominal force of this actuator. All these characteristics will be shown in this paper, and this work will be completed in future.

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10163-90, Session 12B

Effect of electrical terminals made of copper to the ionic electroactive polymer actuators

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In order to diminish the effect of terminals to ionic polymer metal composite (IPMC), the electrical input terminals should be made of a noble metal – platinum or gold. Nevertheless, several published papers report about the results obtained with setups where terminals are made of copper. As a matter of fact, copper is electrochemically not stable enough, even at very low voltages. As soon as a voltage is applied between the terminals, the ions of copper formed in the process of oxidation migrate into the IPMC.

The bending of IPMC actuators is caused by the movement of cations in the applied electric field. In the region of electrical terminals the infiltrated cations of copper will participate in this process, giving additional effect. As a result, close to the input terminals the bending of the IPMC actuator is significantly amplified.

With the help of a showy experiment we compare the bending of an aqueous IPMC material using terminals made of copper and made of gold. We demonstrate that copper contacts:

a) Promote bending close to the terminals

b) Alter the composition of the IPMC between the terminals.

c) Promotes copper dendrites growth into IPMC laminate

10163-91, Session 12B

Fabrication of multilayered conductive polymer structures via selective visible light photopolymerization

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Electropolymerization of pyrrole is commonly employed to fabricate intrinsically conductive polymer (ICP) films that exhibit desirable electromechanical properties. Due to their monolithic nature, electroactive polypyrrole films produced via this process are typically limited to simple linear or bending actuation modes, which has hindered their application in complex actuation tasks. This initiative aims to develop the specialized fabrication methods and polymer formulations required to realize three-dimensional ICP structures capable of more elaborate actuation modes.

Our group has previously reported the application of the digital light processing (DLP) additive manufacturing process for the fabrication of three-dimensional ICP structures using ultraviolet radiation. In this investigation, we further expand upon this initial work and present an improved polymer formulation designed for DLP using visible light, with particular emphasis on enhanced feature size and component homogeneity. The resulting microstructures are characterized to evaluate layer adhesion, surface morphology, feature resolution and electrical conductivity. This technology enables the design of novel electroactive polymer sensors and actuators with enhanced capabilities and brings us one step closer to realizing more advanced electroactive polymer enabled devices.

10163-92, Session 12B

Design and fabrication of conductive polyaniline transducers via computer controlled direct ink writing

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The intractable nature of the intrinsically conductive polymer (ICP) polyaniline (PANI) has largely limited PANI-based transducers to monolithic geometries derived from thin-film deposition techniques. To address this limitation, we have previously reported additive manufacturing processes for the direct ink writing of three-dimensional electroactive PANI structures. This technology incorporates a modified delta robot having an integrated polymer paste extrusion system in conjunction with a counter-ion induced thermal doping process to achieve these 3D structures. In this study, we employ an improved embodiment of this methodology for the fabrication of functional PANI devices with increasingly complex geometries and enhanced electroactive functionality.

Advances in manufacturing capabilities achieved through the integration of a precision pneumatic fluid dispenser and redesigned high-pressure end-effector enable extrusion of viscous polymer formulations, improving the realizable resolutions of features and deposition layers. Fabrication of devices has been further aided by the integration of a multi-material dual extrusion end-effector, enabling passive and active structures to be assembled concurrently, reducing limitations on device geometry. Subsequent characterization of these devices elucidates the relationships between polymer formulation, process parameters, and device design such that electromechanical properties can be tuned according to application requirements.

This methodology ultimately leads to the improved manufacturing of electroactive polymer enabled devices having high-resolution 3D features and enhanced electroactive performance.

10163-93, Session 12B

Adhesion enhancement methods for a roll-to-sheet fabrication process of DE stack-transducers and their influences on the electric properties

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Transducers made of dielectric elastomers (DE) are versatile for many different applications. To gain large strain and forces a stack topology is commonly intended. These DE stack-transducers can be operated as a sensor, a generator or an actuator simultaneously. They can be made of many layers of DE materials, like Silicone (PDMS) and Polyurethane (PUR), stacked on top of each other. These layers are several micrometers thin and coated with a compliant electrode on both sides.

Depending on the application a DE transducer has to withstand tensile forces, which may lead to a delamination of the layers and a ripping of the stack-transducer. This can be prevented by enhancing the adhesion among the layers. A surface plasma jet treatment with an atmospheric plasma beam as well as an adhesive was utilized to obtain an adhesion enhancement. The effects of these methods are introduced briefly. Furthermore, various investigations were made to determine the benefits of the enhancement methods with respect for the electromechanical properties of the electrode. Therefore, many tests regarding the surface resistance of the electrode and the dielectric breakdown strength (DBS) were conducted. The tests indicate that the influences are strongly dependent on the composition of the electrode and the used DE materials of the films. Finally, improvements of a dry deposition roll to sheet manufacturing process for DE stack-transducers can be derived from the obtained results.

10164-1, Session 1

Investigation of flow induced limit cycle oscillations in tensioned ribbons

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Energy harvesting from flow energy using aeroelastic LCO is a relatively new field, which has seen increased research interest over the past decade. It has been shown by researchers that aeroelastic structures comprising of bending and torsional degrees of freedom are capable of exhibiting stable LCO over a wide range of ambient wind speeds suitable for energy extraction. Traditionally aeroelasticians have been working at different methodologies of suppressing aeroelastic instability as it is detrimental to the fatigue life of aircraft structures, leading to catastrophic failures. However, these large amplitude oscillations are desirable for energy harvesting purposes.

The concept of hybrid energy harvesting from solar and wind energy simultaneously has been proposed which aims at harvesting this energy from disparate sources using the same structural element of flexible solar ribbons. This paper looks at flow energy harvesting aspect by predicting the onset of flutter as well as determining the limit cycle amplitude of tensioned ribbons in cross flow. The paper also investigates the sensitivity of the various geometrical parameters affecting the limit cycle amplitude of the structure.

The structural model of the ribbon has been obtained using Transfer Matrix Method, where the ribbon is assumed to have bending and torsional degrees of freedom. For bending degree of freedom. A cubic non-linearity is introduced in the structural model and it is coupled to linear, unsteady aerodyncamics proposed by Peters.

10164-2, Session 1

Comparison of harmonic balance and multi-scale method in characterizing the response of a monostable energy harvester

Wei Wang, Junyi Cao, Jing Lin, Xi'an Jiaotong Univ. (China)

Piezoelectric energy harvesting from ambient vibration to supply electricity for low-power consumption devices has become an international research focus in recent decades due to its high energy density and easily miniaturized fabrication. To overcome the incapability of traditional linear energy harvesters under broadband excitation, theoretical analysis and experimental verification of frequency bandwidth and performance enhancement of harvesters by introducing nonlinear phenomenon have received significant interest. Particularly, bistable, tristable, and monostable oscillators with different types of potential energy functions have been presented to improve the voltage response of these harvesters under broadband excitation. To predict their nonlinear characteristics and draw generalized conclusions regarding performance expectations or design guidelines, harmonic balance method and multi-scale method are popular tools for analytical solution under different excitations. However, the relative accuracy of harmonic balance and multi-scale method in characterizing the response of nonlinear harvester remains uninvestigated. Therefore, new insights into harmonic balance and multi-scale method for solving the response of a monostable energy harvester will be provided through numerical investigation and experimental verification.

Unlike the super-harmonic dynamics appearing in bistable system, the monostable configuration mainly exhibits the first harmonic dynamics. Therefore in this paper, the frequency response function of output voltage for a monostable harvester is derived according to one-term harmonic balance method and the multiscale method with a first-order perturbation respectively. Four order Runge-Kutta method is introduced to numerically simulate the response of the monostable harvester based on the identified model from experiments, in order to compare with the theoretical results obtained from harmonic balance and multiscale method. The output voltage of the monostable harvester under forward and reverse sweep frequency for two acceleration levels 1.5 m/s2 and 3.0 m/s2 are simulated along with the therotical results. It can be seen that the monostable system can generate considerable voltage for a broadband frequency range and it exhibits obvious nonlinear characteristics. Comparisons between numerical simulation and theoretical analysis show that the harmonic balance method is more accuracy to predict the response of the monostable system under different acceleration levels, while the amplitude obtained from multi-scale method has some difference from the simulation results, especially for larger acceleration level. For predicting the cut-off frequency of the monostable system, it is seen that theoretical results obtained from harmonic balance method is very close to the simulation for two acceleration levels. While the cut-off frequency obtained from multiscale method has non-negligible discrepancy with the simulation, especially for larger excitation levels. Moreover, experiments are carried out and the results from simulation and experiments in good agreement under acceleration 1.5 m/s2. In conclusion, the harmonic balance method is more effective to characterizing the response of a monostable energy harvester when compared to multiscale method, especially under larger excitation levels.

10164-3, Session 1

A multiple degree of freedom model of piezoelectret foam in an updated multilayer stack configuration

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Piezoelectric polymers, such as the Emfit polypropylene piezoelectret foam investigated in this study, have distinct advantages over traditional piezoceramics. Although piezopolymers have a smaller piezoelectric coupling coefficient when compared to piezoceramics, they are well suited for in vivo applications, having a lead-free composition, for applications with curved or flexible surfaces, being flexible, or where weight or large shocks are factors, being light weight and resilient. Presented here is both an improved electromechanical multiple degree of freedom (MDOF) model of a multilayer piezoelectret foam stack, including more accurate material properties than the author's previous model, and an updated stack configuration, using lighter, more flexible materials in the stack's construction. The model is based on the author's previous model and predicts the energy harvesting performance of the stack at varying excitation frequencies and for varying stack properties. Finally, the model is also validated against experimental data from the stack with the updated configuration.

10164-4, Session 1

Size effects in piezoelectric cantilevers at submicron thickness levels due to flexoelectricity

Adriane Moura, Alper Erturk, Georgia Institute of Technology (United States)

In elastic dielectrics, piezoelectricity is the response of polarization to applied mechanical strain, and vice versa. Piezoelectric coupling is controlled by a third-rank tensor and is allowed only in materials that are non-centrosymmetric. Flexoelectricity, however, is the generation

of electric polarization by the application of a non-uniform mechanical strain field, i.e. a strain gradient, and is expected to be pronounced at submicron thickness levels, especially at the nano-scale. Flexoelectricity is controlled by a fourth-rank tensor and is therefore allowed in materials of any symmetry. As a gradient effect, flexoelectricity is size dependent, while piezoelectric coupling has no size dependence. Any ordinary piezoelectric cantilever model developed for devices above micron-level thickness has to be modified for nano-scale piezoelectric devices since the effect of flexoelectric coupling will change the electroelastic dynamics at such small scales. In this work, we establish and explore a complete analytical framework by accounting for both the piezoelectric and flexoelectric effects. The focus is placed on the development of governing electro-elastodynamic piezoelectric-flexoelectric equations for the problems of energy harvesting, sensing, and actuation. The coupled governing equations are analyzed to obtain the frequency response. The coupling coefficient for the bimorph configuration is identified and its size dependence is explored.

10164-5, Session 1

Uncertainty propagation in piezoelectric energy harvesting

Heonjun Yoon, Yong Chang Shin, Soo-Ho Jo, Byeng D. Youn, Seoul National Univ. (Korea, Republic of)

Piezoelectric energy harvesting is known to be a practical solution in converting vibration energy into usable electricity since it can be easily miniaturized in a wireless sensor. For designing a piezoelectric energy harvester, it is essential to develop a high-fidelity electromechanical model which predicts its output power under various vibration conditions. However, one challenge is to accurately predict the output power in the presence of uncertainty. Input uncertainties in the material properties and geometry are propagated to the variation of the output power. Unless the input uncertainties are properly addressed, the output power generated by the piezoelectric energy harvester will vary, thereby leading to unreliable prediction. We thus present a comprehensive framework for quantifying the variation of the output power propagated from the input uncertainties, namely as the uncertainty propagation. The statistical moments of the output power are estimated by integrating the probabilistic analysis techniques and electromechanical model. The statistical model calibration is performed to improve the predictive-capability of the electromechanical model. The statistics of unknown random variables in the electromechanical model are inferred while maximizing the likelihood between the predicted and measured performances. Once the electromechanical model becomes statistically valid, we can use it proactively in designing the piezoelectric energy harvester.

10164-6, Session 2

Thermal stress characterization using the electro-mechanical impedance method

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This study examines the potential of the Electro-Mechanical Impedance (EMI) method to provide an estimation of the developed thermal stress in constrained bar-like structures. This non-invasive method features the easiness of implementation and interpretation, while it is notoriously known for being vulnerable to environmental variability. A comprehensive analytical model is proposed to relate the measured electric admittance signatures of the PZT element to temperature and uniaxial stress applied to the underlying structure. The model results compare favorably to the experimental ones, where the sensitivities of features extracted from the admittance signatures to the varying stress levels and temperatures are determined. Two temperature compensation frameworks are proposed to characterize the thermal stress states: (a) a regression model is established based on temperature-only tests, and the residuals from the thermal stress tests are then used to isolate the stress measurand; (b) the temperature-only tests are decomposed by Principle Components Analysis (PCA) and the feature vectors of the thermal stress tests are reconstructed after removal of the temperature-sensitive components. For both methods, the features were selected based on their performance in Receiver Operating Characteristic (ROC) curves. Experimental results on the Continuous Welded Rails (CWR) are shown to demonstrate the effectiveness of these temperature compensation methods.

10164-7, Session 2

Investigation into the superposition of multiple mode shape composed traveling waves

Patrick Musgrave, V. V. N. Sriram Malladi, Pablo A. Tarazaga, Virginia Polytechnic Institute and State Univ. (United States)

Structural traveling waves have potential applications in numerous areas such as propulsion and skin friction drag reduction. Recent research has shown that via the two-mode excitation method, traveling waves can be generated in both 1D and 2D structures via the use of low-profile piezoelectric actuators. This research has been extended to show that multiple frequency traveling waves can be simultaneously generated on 1D beams by superimposing the individual waves. However, when exciting traveling waves in a 2D structure, the waves no longer propagate uniformly across a surface as in the 1D case. The resultant propagation patterns can include unidirectional traveling waves with spatial phase shifts, wave fronts moving in opposing directions, or rotationally moving waves. These propagation patterns depend on the participating modes and vary based on the excitation frequency, thus when generating multiple frequency traveling waves in a 2D structure multiple propagation patterns are superimposed. The result is that a single 2D structure can have areas with collinear waves, areas with opposing waves, and areas with perpendicular waves, all simultaneously. This study focuses upon experimentally determining the types of propagation patterns that result when generating multiple frequency traveling waves in a 2D structure.

10164-9, Session 2

Camera image processing for automated crack detection of pressed panel products

Hoyeon Moon, Hwee Kwon Jung, Chang Won Lee, Gyuhae Park, Chonnam National Univ. (Korea, Republic of)

Crack detection on pressed panel during the press forming process is an important step to ensure the quality of panel products. Traditional crack detection technique has been generally performed by experienced human inspectors, which is subjective and expensive. Therefore, the implementation of automated and accurate crack detection is necessary during the press forming process. In this study, we performed an optimal camera positioning and automated crack detection using two image processing techniques with multi-view-camera system. The first technique is based on evaluation of the panel edge lines which are extracted from a percolated object image. This technique does not require a reference image for crack detection. Another technique is based on the comparison between a reference and a test image using the local image amplitude mapping. Before crack detection, multi-view images of a panel product are captured using multiple cameras and 3D shape information is reconstructed. Optimal camera positions are then determined based on the shape information. Afterwards, cracks are automatically detected using two crack detection techniques based on image processing. In order to demonstrate the capability of the proposed technique, experiments were performed in the laboratory and the actual manufacturing lines with the real panel products. Experimental results show that proposed techniques could effectively improve the crack detection rate with improved speed.

10164-10, Session 2

Development of pulse-echo ultrasonic propagation imaging system and its delivery to Korea Air Force

Seung-Chan Hong, Hasan Hamid, Ayalsew Dagnew, Jung-Ryul Lee, KAIST (Korea, Republic of)

This study introduces development history of a mobile version of full-field pulse-echo ultrasonic propagation imaging (PE UPI) system for the delivery to Korea Air Force. The PE UPI system is an in situ nondestructive evaluation (NDE) equipment based on laser ultrasonics. The requirements for the field application defined by Korea Air Force are presented and how we met each requirement is introduced as well. The system works by detection of bulk waves that travel through the thickness of a specimen. This enables accurate and clear damage assessment and defect localization in the thickness with minimum signal. The system consists of a Q-switched laser for generating the aforementioned waves, a Doppler vibrometer for sensing, optical elements to combine the generating and sensing laser beams, a dual-axis automated translation stage for raster scanning of the specimen and a digitizer to record the signals. A GUI is developed to control all the individual blocks of the system. Additionally the software also manages signal acquisition, processing and display. The GUI is created in C++ using QT framework. In view of the requirements posed by the Korea Air force, the system is designed to be compact and portable to allow for in situ NDE of a selected area of an in-service aircraft. The GUI is designed with a minimalistic approach to promote usability and adaptability sans intricacies of actual system operation. A multithreading algorithm can show the results in real time while a specimen is being scanned.

10164-11, Session 3

Passive damping of carbon fiber reinforced plastic with interlaminar enhanced PZT particles dispersed epoxy resin film

Jaemin Jung, Woo Il Lee, Dasom Lee, Gyu Hee Lee, Young Chul Shin, Seoul National Univ. (Korea, Republic of)

Carbon fiber reinforced plastic (CFRP) has been applied various fields which like automotive, aerospace, and leisure/sports industries, because of high strength, light weight, corrosion resistance and other properties. In order to enhancing the inherent low damping property of CFRP, lead zirconate titanate (PZT) ceramic particles which is one of typical piezoelectric material dispersed in CFRP laminate. The PZT particles dispersed into inerlaminar of CFRP improve the vibration damping ability by converting vibrational energy into thermal energy and electrical energy. However, to maximize the advantage of PZT particles as a passive damping material, they must be well dispersed in interlaminar of CFRP. In this study, the epoxy resin films which contains well dispersed PZT particles are made for inserting into CFRP laminate. The resin films are manufactured several concentrations of PZT particles. To compare the damping, the CFRP samples which is fabricated by hand lay-up of PZT particles are also manufactured. Dynamic mechanical analyzer (DMA) which is employed to measure the loss factor (tanδ) of a material to verify the change in vibration damping. The results show that there exists significant difference on vibration damping ability between them.

10164-12, Session 3

Piezoelectrically strained bistable laminates with macro fiber composites

Andrew Lee, Amin Moosavian, Daniel J. Inman, Univ. of Michigan (United States)

The bistability and snap through capability of an unsymmetric laminate consisting of only Macro Fiber Composites are investigated. The non-linear analysis predicts two cylindrically stable configurations when strain anisotropy is piezoelectrically induced within a [0MFC/90MFC]T laminate. This is achieved by bonding two MFC's in their actuated states and releasing the voltage post cure to create in-plane residual stresses. The minimization of total potential energy with the Rayleigh-Ritz method are used to analytically model the resulting laminate. A finite element analysis is conducted in MSC Nastran using the piezoelectric-thermal analogy approach to verify the analytical results. The effects of adhesive properties, bonding cure cycles, MFC layup, and its geometry on the curvatures, strains, displacements, and bifurcation voltages are characterized. Finally, the snap through and reverse snap through capabilities with piezoelectric actuation are demonstrated. This adaptive laminate functions as both the actuator and the load bearing structure and allows large deformations under a non-continuous energy input. Its snap through capability allows full configuration control necessary in morphing applications.

10164-13, Session 3

Parametric study of fluid flow manipulation with piezoelectric macro-fiber composite flaps

Omidreza Sadeghi, Pablo A. Tarazaga, Mark Stremler, Shima Shahab, Virginia Polytechnic Institute and State Univ. (United States)

Active Fluid Flow Control (AFFC) has received great research attention due to its significant potential in engineering applications. It is known that drag reduction, turbulence management, flow separation delay and noise suppression through active control can result in significantly increased efficiency of future commercial transport vehicles and gas turbine engines. In microfluidics systems, AFFC has mainly been used to manipulate fluid passing through the microfluidic device. We put forward a conceptual approach for fluid flow manipulation by coupling multiple vibrating structures through flow interactions in an otherwise quiescent fluid. Previous investigations of piezoelectric flaps interacting with a fluid have focused on a single flap. In this work, arrays of closely-spaced, free-standing piezoelectric flaps are attached perpendicular to the bottom surface of a tank. The coupling of vibrating flaps due to their interacting with the surrounding fluid is investigated in air (for calibration) and under water. Actuated flaps are driven with a harmonic input voltage, which results in bending vibration of the flaps that can work with or against the flow-induced bending. The size and spatial distribution of the attached flaps, and the phase and frequency of the input actuation voltage are the key parameters to be investigated in this work. Our analysis will characterize the electrohydroelastic dynamics of active, interacting flaps and the fluid motion induced by the system. Particular attention will be given to determining inertia and drag terms that can be used to model the coupled motion in practical applications.

10164-14, Session 3

Hybrid passive-active modal networks for structural acoustic control

Kenneth A. Cunefare, Georgia Institute of Technology (United States); Boris Lossouarn, Conservatoire National des Arts et Métiers (France); Manuel Collet, Ecole Centrale de Lyon (France)

Distributions of piezoelectric patches bonded to structures provide a means to alter or control, through active or passive means, the dynamic response of the host structure. Numerous active control schemes for such composite structures have been explored. Alternatively, for certain structures, a passive electrical network may be implemented which presents an electrical analog of the modal response of the structure, effectively providing a

multi-modal, distributed passive tuned mass modal damper capability. Numerous tuned-mass damper design concepts ("tunings") may be applied to such a passive network. Further, the distributed network analog, when coupled with active control concepts, permits a hybrid distributed passive-active modal control capability. This paper explores this hybrid distributed network control concept applied to a clamped rectangular plate. A unit-cell discrete representation of the plate leads to an electrical analog comprised of passive inductors, transformers and resistors. Addition of synthetic (or controlled) impedances at a limited set of points within the network permits dynamic adjustment of the frequency response of the system.

10164-15, Session 3

Low-weight, high-stiffness glass fiber reinforced polymer beams with embedded piezoelectric fibers

John A. Gallagher, Roselita Fragoudakis, Merrimack College (United States)

This work presents a theoretical study of the effects on stiffness and deflection of embedding piezoelectric fibers within glass fiber reinforced polymer (GFRP) beams. Through this study, enhancements to the beam stiffness and flexural capabilities are analyzed as a result of the piezoelectric effect of the embedded piezoelectric fibers. Fiber orientation of GFRP laminated beams is optimized based on stiffness requirements following classical lamination theory. A finite element model with a micromechanical-based constitutive law is developed to assess the piezoelectric effect on the GFRP beam. The symmetric unidirectional general stacking sequence laminates are shown to have optimal stiffness and deflection behavior. The addition of piezoelectric fibers with d333 piezoelectric actuation mode (longitudinally down the length of the beam) further increases stiffness and reduces deflection. This enables tuning of the mechanical properties of the laminate beam. A model of the bulk behavior was developed using Autodesk Inventor. The effect of piezoelectric fiber orientation within the laminate was simulated using Autodesk Simulation Mechanical. Introducing piezoelectric fibers to the reinforcing phase further optimizes the deflection range under bending while additionally minimizing the structure's weight. The strengthening effect of the piezoelectric fibers reduces the required number of laminate layers while maintaining optimal behavior. The effect of the embedded piezoelectric fibers on the transverse stiffness of the laminate is also investigated and evaluated.

10164-16, Session 3

Evaluating the performance of an advanced smart needle prototype inside tissue

Bardia Konh, Minji Jo, Univ. of Hawai'i at Manoa (United States)

In this work, our previously designed and developed smart needle has been evaluated inside the tissue. This prototype was particularly designed to cause minimum damage to the tissue during activation. This prototype includes a flexible joint element that would introduce a higher maneuverability for the structure.

The smart needle has been inserted into a gel material that mimics the characteristics of the real tissue using a linear motorized stage. The needle tip position has been estimated using both imaging techniques and an electromagnetic tracking device.

The amount of power required for a certain deflection was reported and the effects of having different length and stiffness of the joint element were reported. The amount of deflection obtained by this smart needle with symmetrical tip has been compared with the same size of passive needles with different bevel tip angles. The amount of tissue rupture during the activation time was also estimated in this work. A tradeoff analyses were done to illustrate the benefits and discuss the disadvantages of using either active or passive needles. It was shown that the amount of deflection provided by our smart needle is much higher than the maximum deflection reachable with passive needles with any bevel tip angles.

It was also demonstrated that a path with a very small radius of curvature could be followed if a sharp bevel tip angle is embedded at the smart needle tip. The combination of both provides an easier way to maneuver around anatomical obstacles inside the human body on the way reaching the target locations.

10164-17, Session 3

Generating additional resonances: adding a twist to the split ring resonator

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In this proceeding we present a novel method for adding an additional resonance to the split ring resonator (SRR). Developed by Pendry, et. al. in 1999[1], the SRR structure pioneered the field of metamaterials. By printing a periodic planar array of metallic SRR elements, a person can generate materials with effective permittivities and permeabilities not found in nature. However, due to the planar nature of these structures, they can be limited in their ability to interact with radiation of oblique incidence. Here we introduce a structure capable of interacting with such polarizations through an out-of-plane bend. The structure is a folded triangular split ring resonator (TSRR). Typically, a TSRR supports either an electric or magnetic resonance depending upon the polarization of the incident radiation. As we will show, our structure is capable of supporting an additional resonance by inducing a current in the bend due to an axial magnetic field. With all resonances, the resonant frequency will correspond to the structure's size. Due to the small size of the bend, the resonant frequency is quite high for such a large structure. However, we show that this frequency can be shifted by altering the size of the bend.

[1] Pendry, John B., et al. "Magnetism from conductors and enhanced nonlinear phenomena." IEEE transactions on microwave theory and techniques 47.11 (1999): 2075-2084.

10164-18, Session 4

Design and simulation on the morphing composite propeller

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As one of the most crucial part of the unmanned underwater vehicle (UUV), the composite propeller plays an important role on the UUV's performance. As the composite propeller behaves excellent properties in hydroelastic facet and acoustic suppression, it attracts increasing attentions all over the globe. This paper goes a step further based on this idea, and comes up with a novel concept of "morphing composite propeller" (MCP) to improve the performance of the conventional composite propeller (CCP) to anticipate the improved propeller can perform better to propel the UUV. Based on the new concept, a novel MCP is designed. Each blade of the propeller is assembled with an active rotatable flap (ARF) to change the blade's local camber with flap rotation. Then the transmission mechanism (TM) has been designed and housed in the propeller blade to push the ARF. With the ARF rotating, the UUV can be propelled by different thrusts under certain rotation velocities of the propeller. Based on the design, the Fluent is exploited to analyze the fluid dynamics around the propeller. Finally, based on the design and hydrodynamic analysis, the structural response for the novel morphing composite propeller is calculated. The propeller blade is simplified and layered with composite materials. And the structure response of an MCP is obtained with various rotation angle under the hydrodynamic pressure. This simulation can instruct the design and fabrication techniques of the MCP.

10164-19, Session 4

Experimental testing of a planform and camber morphing horizontal tail

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A bird's tail plays a crucial role in flight dynamics by making rapid fine-tuned movements for precise attitude stabilization in addition to large scale deformations used in conjunction with the wings to achieve prolonged maneuvers. However this geometry differs substantially from the geometry of traditional aircraft control surfaces like the vertical rudder which has slower actuation times, less versatility regarding control authority, and increased radar signature. By expanding on previous designs, this work aims to increase maneuverability and stability in tailless UAVs using Macro Fiber Composites (MFCs), shape memory alloy (SMA) wires, and multi-material 3D printing to achieve a planform and camber morphing horizontal tail. The MFCs are customized with a 55° fiber orientation to achieve bending-twisting coupling resulting in complex curvatures. This allows for yaw control across large sideslip angles, pitch control, and air brake control. The SMA wires are incorporated in a hinge design to change the planform area which increases the size of the control surface, making it more effective when needed but minimizing drag elsewise. A 3D printed multi-material substrate combining both flexible honeycomb and sliding surfaces is developed to achieve changes in planform area while still allowing for camber morphing deformations from the MFCs. The actuation capabilities are evaluated without aerodynamic load, and initial aerodynamic testing is conducted to characterize the actuation range under aerodynamic loading.

10164-20, Session 4

Numerical and experimental study of bistable plates for morphing structures

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This study is concerned with the activation energy threshold of bistable composite plates in order to tailor a bistable system for specific aeronautical applications. The aim is to explore potential configurations and their dependencies on material and geometric parameters for designing novel morphing structure suitable for aerodynamic surfaces. The bistable laminates have two stable mechanical shapes that are able to withstand aerodynamic loads without any additional constraint forces or locking mechanisms. This kind of structures, when properly loaded, snap-through from one stable configuration to another, causing large strains. A strain energy formulation gives way to a compact set of governing equations of deformation, which can be solved in closed form in order to identify energetic activation thresholds for particular boundary conditions. In this manner, the transition between the stable states of the composite laminate can be triggered simply by aerodynamic loads (pilot, disturbance or passive inputs) without the need of servo-activated control systems. Both numerical simulations based on Finite Element models and experimental testing based on different activating forcing spectra were used to validate this concept. The results show that, for proper configurations of constraints, materials and geometric parameters, bistable plates can be successfully used as aircraft passive wing flaps.

10164-21, Session 4

Drag reduction in turbulent flow using spanwise traveling surface waves

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In most systems, friction drag is an obstacle to be hurdled and is a large source of energy inefficiency in airplanes, ships, pipes, etc. By reducing the amount of friction drag between a fluid and a surface, large energy savings are possible. In turbulent flow, over a surface, a large portion of the friction drag results from vortical structures that increase the shear stress on the surface. Previous research has shown that traveling waves propagating in the spanwise direction (perpendicular to flow) interfere with that vortex production. As a result, the friction drag resulting from the shear stress is decreased and reductions of greater than 10% are achievable. However, previous research relied on discrete, highly intrusive actuators that can only generate waves at limited frequencies and wavelengths. The two-mode excitation method of traveling wave generation uses low-profile piezoelectric actuators that rely on the structural properties of the continuous media to generate traveling waves without parametric limitations. This study uses the two-mode excitation method to generate traveling waves at various frequencies and amplitudes in an open-loop wind tunnel to experimentally determine the drag reduction in turbulent flow.

10164-106, Session 4

The application of thermal morphing anisogrid smart space structures for high precision applications

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To achieve the thermal and structural stability required by current spacecraft systems, large heavy static structures are used in conjunction with secondary intelligent adaptive systems. This paper investigates the morphing capability of a system where thermal gradients are applied to introduce an active morphing control capability into the originally passive primary structure. This lightweight, flexible, intelligent primary structure is able to achieve the design requirements by actively adapting to the on orbit environment rather than by passive means. This concept has the potential to reduce mass and provide improved performance enabling new applications and structural architectures. Previous work has developed performance metrics and investigated the minimum morphing capability of this concept for a 1 meter long boom. This paper expands on the previously detailed Thermal Morphing Anisogrid Structure by improving modeling accuracy and addressing some of the secondary performance characteristics of interest. The key challenges to be addressed in this paper are the power requirements, the restorative force capability, alternate design points, and finally the degradation of morphing quality due to conductive losses.

10164-22, Session 5

Wave manipulation using adaptive elastic metamaterial with piezoelectric circuitry

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Metamaterial exhibits a number of attractive abilities such as frequency filtering, wave guiding, wave focusing, etc. Conventionally, the realization of the metamaterial is through the carefully design of mechanical unit cell in a periodic structure. However, the functionalities of this kind of metamaterial are limited. In this paper, distributed piezoelectric transducers interconnected with periodic electric circuitry, i.e. electrical transmission line, are integrated onto the host structure, which forms an electromechanically periodic structure. The energy flow or distribution inside the host structure can be manipulated by adaptively adjusting the circuital elements of the transmission line coupled with the host structure via the piezoelectric transducers under different circumstances. A numerical model based on the transfer matrix methodology and Bloch theory are built to predict the bang gaps and attenuation factors as well as the transmission of vibration in the proposed adaptive metamaterials. Influences of different electric networks on wave propagation and attenuation in terms of the propagation constants are studied.

10164-23, Session 5

Design and experimental validation of an adaptive phononic crystal using highly dissipative polymeric material interface

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Periodic structures exhibit very specific properties in terms of wave propagation. This topic has interested researchers over the years, and a growing activity on this field is observed on the last years, with the objective of designing structures exhibiting properties that conventional ones cannot possess. The methods currently used are most of the time based on those derived from wave propagation in crystals, where almost no dissipation occurs. Reaching the upper scale for structural dynamics implies that damping effects have to be included in the analyses which are performed. In this paper, some numerical tools for dispersion analysis of periodic structures are presented, with a focus on the ability of the methods to deal with dissipative behavior of the systems. An adaptive phononic crystal based on the combination of metallic parts with highly dissipative polymeric interface is designed. The system consists in an infinite periodic bidirectional waveguide, namely a 1 mm thick Aluminum plate with periodic cylindrical pillars. The pillars include a layer of shape memory polymer and Aluminum. The mechanical properties of the polymer depend on both temperature and frequency and can radically change from glassy to rubbery state, with various combination of high/low stiffness and high/low dissipation. A fractional derivative Zener model is used for the description of the frequency-dependent behavior of the polymer. A 3D finite element model of the cell is developed for the design of the metamaterial. The "Shifted-Cell Operator" technique consists in a reformulation of the PDE problem by "shifting" in terms of wave number the space derivatives appearing in the mechanical behavior operator inside the cell, while imposing continuity boundary conditions on the borders of the domain. Damping effects can easily be introduced in the system and a quadratic eigenvalue problem yields to the dispersion properties of the periodic structure. In order to validate the design and the adaptive character of the metamaterial, results issued from a full 3D model of a finite structure embedding an interface composed by a distributed set of the unit cells are presented. Various driving temperature are used to change the behavior of the system. After this step, a comparison between the results obtained using the tunable structure simulation and the experimental results is presented. Two states are obtained by changing the temperature of the polymeric interface: at 20°C, the band gap is visible around a selected frequency. Above the glass transition, the phononic crystal tends to behave as an homogeneous plate.

10164-24, Session 5

Investigations on an EAP-based tunable Helmholtz resonator

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A Helmholtz resonator is a passive acoustic resonator used to control a single frequency resulting from the cavity volume and the resonator neck size. The aim of the proposed study is to present a new concept and strategy allowing real-time tunability of the Helmholtz resonator in order to enhance acoustic absorption performances in lower frequencies (<500 Hz). The proposed concept consists in replacing the resonator rigid front plate by an electroactive polymer (EAP) membrane. When an electric field is applied, a change is made in the EAP membrane mechanical properties which induce a resonance frequency shift. Well located springs could direct the membrane deformation following the axis of the resonator to obtain a cavity volume variation. Both strategies allow variation of the resonance frequencies of the device. Experimental measurements are performed to determine the potential of this concept for improvement of low-frequency performances of acoustic absorption devices.

10164-25, Session 5

Acoustic design of boundary segments in aircraft fuselages using topology optimization and a specialized acoustic pressure function

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In most aviation applications, a major cost benefit can be achieved by a reduction of the system weight. Often the acoustic properties of the fuselage structure are not in the focus of the primary design process, too. A final correction of poor acoustic properties is usually done using insulation mats in the chamber between the primary and secondary shell. It is plausible that a more sophisticated material distribution in that area can result in a substantially reduced weight. Topology optimization is a well-known approach to reduce material of compliant structures. In this paper an adaption of this method to acoustic problems is investigated. The gap full of insulation mats is suitably parameterized to achieve different material distributions. To find advantageous configurations, the objective in the underlying topology optimization is chosen to obtain good acoustic pressure patterns in the aircraft cabin. An important task in the optimization is an adequate Finite Element model of the system. This can usually not be obtained from commercially available programs due to the lack of special sensitivity data with respect to the design parameters. Therefore an appropriate implementation of the algorithm has been done, exploiting the vector and matrix capabilities in the MATLAB® environment. Finally some new aspects of the Finite Element implementation will also be presented, since they are interesting on its own and can be generalized to efficiently solve other partial differential equations as well.

10164-26, Session 5

Characterization of carbon black-filled magnetorheological elastomer under combined shear and compression loads

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This study presents the effect of compression force on the shear fore-displacement properties of carbon black-filled magnetorheological elastomer (MRE). ASTM standard anisotropic MREs with silicone matrix and carbon black fillers are fabricated and their properties are compared with carbon black filled natural rubber-based isotropic MREs. The mechanical properties of the MREs are investigated in a combined shear and compression double-lap test setup capable of applying a magnetic field. Effect of different loading conditions such as shear and axial load levels, loading frequency, and magnetic field on the shear modulus of MRE are presented. Experimental results show that adding carbon black improves not only the modulus of MRE but also the MR effect and. Also, it is shown that anisotropic MREs exhibit an enhanced MR effect under a simultaneous axial force.

10164-27, Session 6

Modeling of a reinforced concrete beam using shape memory alloy as reinforcement bars

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In this paper the structural behavior of reinforced concrete (RC) beams with smart rebars under three point loading system has been numerically studied, using Finite Element Method. The material used in this study is Superelastic Shape Memory Alloys (SE SMAs) which contains nickel and titanium. Shape memory alloys (SMA) are a unique class of materials which have ability to undergo large deformation and also regain its undeformed shape by removal of stress or by heating. In this study, a uniaxial SMA model able to reproduce the pseudo-elastic behavior for the reinforcing SMA wires. Thus, finite element simulations are developed in order to reproduce the load-deflection behavior of smart concrete beams subjected to three-point bending tests.

1. INTRODUCTION

In recent years, the dream of designing and constructing smart structures is becoming a reality. Civil engineers with the help of metallurgical science have created innovative structural materials which can display predetermined physical characteristics.

Shape Memory Alloys (SMAs) are a novel functional material which can exhibit little residual strains under cycles of loading and unloading even after passing the yielding zone. They have the ability to remember a predetermined shape even after severe deformations which enable them to be widely used in numerous applications in the area of 'smart materials' or 'intelligent materials' [1-4].

In 1965, shape memory alloys (Nitinol) which derived from Nickel and Titanium were first patented by Buehler and Wiley [5] in Naval Ordnance Laboratory. Depending on the temperature, SMA can be austenite, martensite or the mixture of them. Indeed, these alloys are particularly useful when large deformation and recovery of the shape is observed under a small rate of stress or temperature.

In recent years, the two major properties of SMAs have attracted the attention of many researches for application to smart structural systems. One is the shape memory effect (SME), in which a specimen exhibits a larger residual strain after loading and unloading that can be fully recovered upon raising the temperature of the material. This recovery stress can be used for introducing forces in structures. The other important phenomenon is the superelastic effect (SE), in which a specimen achieves a very large strain by the phase transformation from austenite to martensite upon loading that is then fully recovered in a hysteresis loop upon unloading and without the changing the temperature. Besides, both SME and SE are caused by phase transformation.

In the present study, finite element analysis of reinforced concrete beams using smart rebar were performed to investigate the effect of ratio of SMA rebars, and strength of concrete on the behavior of RC beams embedded with SMA wires. Both characteristics of materials and finite element model are described. Then, results of analysis using ANSYS software are presented and discussed.

2. Characteristics of Materials

Concrete

The modeling of concrete considers cracking, crushing failure modes and nonlinear behavior. Also the elastic modulus and Poisson's ratio are 20 GPa and 0.2, respectively. The concrete material was model in the ANSYS.

Steel

Bilinear stress-strain curve has been used for the modeling of steel behavior. The values of elastic modulus and Poisson's ratio of steel are 200 GPa and 0.3, respectively. The model, which introduces the behavior of steel in nonlinear form, is based on the model of Bilinear Kinematic Hardening. The steel is assumed to have yield strength of 400 MPa.

Shape Memory Alloys

In order to model SMA in ANSYS software, the predetermined nonlinear model, which is provided in material library, has been used here. This model is used for describing the superelastic effect of NiTi-based alloys as well. The term SE refers to a recovery of the large deformations in loading-unloading cycles, occurring at the certain temperatures. Furthermore, the capability of these classes of materials in recovering the possible accumulated deformations by heat treatment is called SME.

Figure 1 shows the stress-strain relationship for the SMA which has been used in ANSYS software. In this figure, ?s AM and ?f AM are starting and final stresses for the forward transformation (austenite to martensite) respectively, ?s MA and ?f MA are starting and final stresses for the reverse transformation (martensite to austenite) respectively, EA is the elastic modulus of the austenite phase, and L is the maximum residual phase. The values of these parameters are also listed in table1.

3. Geometrical Modeling

A RCC beam with three-point bending load case was taken for analysis as shown in the figure with: the size of the reinforced concrete beam: 100 mm x 100 mm; size of loading and; SMA reinforcement details: 5 rebar's of 2mm ϕ at bottom, stirrups of 2 legged 2 mm ϕ. as shown in Fig. 2.

4. Characteristics of Finite Element Model

Regarding concrete model meshes, it is noticeable that by using SOLID 65 element the nonlinear behavior and also the capability of cracking and crushing of the concrete have been considered. In ANSYS software, SMAs can be specified for the following elements: PLANE182, PLANE183, SOLID185, SOLID186, SOLID187, and SOLSH190.

The most suitable elements for 3-D rebar modeling are SOLID elements. Besides, the number of node and order are the same in both elements SOLID185 and SOLID 65. Since the details of both SMA and steel reinforcement must be changed frequently, using SOLID185 element for the entire reinforcements provides high speed during modeling process. LINK180 element has been used here for stirrups modeling of concrete beam.

5. Loading and Boundary Conditions

Displacement boundary conditions are needed to constrain the model to get a unique solution. The beam was simply supported with one end was hinged while another was kept as roller. The force, P, applied at the steel plate is applied across the entire centerline of the plate as shown in figure.

6. Analysis

The finite element model for this analysis is a simple beam under transverse loading. For the purposes of this model, the static analysis type is utilized.

7. RESULTS

The main aim to model a reinforced concrete beams with SMA bars was to observe the recovery of a structure subjected to three-point bending test. The minor errors in results may be due to the fault of the modeling. Finally, this gave confidence in the use of ANSYS 15.0 and the model developed.

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10164-28, Session 6

SMA spring-based artificial muscle actuated by hot and cool water using faucet-like valve

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An artificial muscle for a human arm-like manipulator with high strain and high power density are under development, and an SMA(Shape memory alloy) spring is a good actuator for this application. In this study, an artificial muscle composed of a silicon tube and a bundle of SMA(Shape memory alloy) springs is evaluated. A bundle of SMA springs consists of 5 SMA springs which are fabricated by using SMA wires with a diameter of 0.5 mm, and hot and cool water actuates it by heating and cooling SMA springs. A faucet-like valve was also developed to mix hot water and cool water and control the water temperature. The mass of silicon tube and a bundle of SMA springs is only 3.3 g and 2.25 g, respectively, and the total mass of artificial muscle is 5.55 g. It showed good actuating performance for a load with a mass of 2.3 kg and the power density was more than 500 W/kg for continuous valve switching with a cycle of 0.6 s. The faucet-like valve can switch a water output from hot water to cold water within 0.3s, and the artificial muscle is actuated well in response to the valve position and speed. It is also presented that the temperature of the mixed water can be controlled depending on the valve position, and the displacement of the artificial muscle can be controlled well by the mixed water. Based on these results, SMA spring-based artificial muscle actuated by hot and cool water could be applicable to the human arm-like robot manipulators.

10164-29, Session 6

Smart Registers for Automated Building Energy Saving (SRABE)

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The new era in energy-efficiency building is to integrate automatic occupancy detection with automated heating, ventilation and cooling (HVAC), the largest source of building energy consumption. By closing off some air vents, during certain hours of the day, up to 7.5% building energy consumption could be saved.

In the past, smart vent has received increasing attention and several products have been developed and introduced to the market for building energy saving. For instance, Ecovent Systems Inc. and Keen Home Inc. have both developed smart vent registers capable of turning the vent on and off through smart phone apps. However, their products do not have on-board occupancy sensors and are therefore open-loop. Their vent control was achieved by simply positioning the vent blade through a motor and a controller without involving any smart actuation.

This paper presents an innovative approach for automated vent control and automatic occupancy (human subjects) detection. We devise this approach in a smart register that has polydimethylsiloxane (PDMS) frame with embedded Shape memory alloy (SMA) actuators. SMAs belong to a class of shape memory materials (SMMs), which have the ability to 'memorise' or retain their previous form when subjected to certain stimulus such as thermomechanical or magnetic variations. And it can work as actuators and be applied to vent control. Specifically, a Ni-Ti SMA strip will be pre-trained to a circular shape, wrapped with a Ni-Cr resistive wire that is coated with thermally conductive and electrically isolating material. Then, the SMA strip along with an antagonistic SMA strip will be bonded with PZT sensor and thermal sensors, to be inserted into a 3D printed mould which will be filled with silicone rubber materials. In the end, a demoulding process yields a fully integrated blade of the smart register.

Several blades are installed together to form the smart register. The PZT sensors can feedback the shape of the actuator for precise shape and air flow control. The performance and the specification of the smart registers will be characterized experimentally. Its capacity of regulating airflow, forming air curtain will be demonstrated.

10164-30, Session 6

Use of shape memory polymer composite hinges for self-deploying antenna

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In this study, a self-deploying antenna for outer space is designed with the actuation of a shape memory polymer composite (SMPC) hinges. The kinematic design how to activate the deployment of folded antenna with SMPC hinges is investigated. Carbon fiber fabric reinforced SMPC hinges were fabricated for experiment purpose and studied the behavior of SMPC on the process of thermal-responsive. The SMPC hinge specimens with four plies of carbon fiber fabric and a shape-memory polymer were prepared for the experiment. The glass transition temperature was determined using dynamic mechanical analysis (DMA 800). Furthermore, a SMPC hinge has been manufactured and then tested packaging/deploying ability and a computer model of self-deploying antenna using that SMPC hinge has been developed for fabricating.

10164-31, Session 6

Characterization of coiled SMA actuators for humanoid robot

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Previously, we have presented the design and characterization of artificial heart using cylindrical shape memory alloy (SMA) actuators [1] and SMA coiled spring actuators for humanoids [2] . The robotic heart was primarily designed to pump a blood-like fluid to parts of the robot such as the face to simulate blushing or anger by the use of elastomeric substrates for the transport of fluids. In this paper, we want to present our results of modeling and characterization of coiled spring SMA spring actuators which were used in the previous publication [2]. We want to develop a theoretical model to describe the behavior of our SMA coiled springs based on the constitutive model of SMA. We also want to experimentally verify our developed theoretical model and analyze various parameters like shear stress and spring constant with respect to temperature during actuation.

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10164-32, Session 6

Finite element analyses of a dual actuated prototype of a smart needle

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Brachytherapy is known as a highly popular procedure to cure the prostate cancer. In this procedure radioactive seeds are being placed very close to the tumor to kill it locally. Since the radioactive dosage could easily damage the healthy tissue as well, it has to be certainly assured that these seeds

are being released at the exact locations of the cancerous cells. The passive straight needles of conventional procedures don't normally let the surgeons to compensate for their possible errors. The smart needles actuated by shape memory alloy (SMA) wires are recently being introduced to provide more actuation and control for the surgeons.

In our recent work, a prototype of a smart needle was reported where not only the actuation of SMA wires were incorporated, but also shape memory polymers (SMPs) were included in the design introducing a soft joint element to further assist the accuracy and flexibility of the active surgical needles. This work presents the finite element studies of this prototype.

The additional actuation of shape memory polymers provided the capability of reaching very high deflections that were not possible to achieve before. However, there are some disadvantages using this active SMP component compared to a passive nylon joint element that are discussed in this work. The deflection of the smart needle has been evaluated by a magnetic tracing system and has been compared with our numerical results. The utilization of SMPs as soft joint elements showed 15% improvement in the final needle tip deflection.

10164-33, Session 6

Design, fabrication, and environmental testing of shape memory alloy-based composite morphing radiator

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Upcoming crewed space missions will require management of large internal and external heat loads, necessitating advanced thermal control systems to maintain a certain environment. Radiators with at least 10:1 turndown ratios (the ratio between the maximum and minimum heat rejection rates) will be needed; however, current technologies are only able to achieve turndown ratios of approximately 3:1. A morphing radiator capable of altering shape and the configuration of exposed surfaces could significantly increase turndown capabilities. Shape memory alloys offer qualities that may be well suited for this endeavor; their temperature-dependent phase changes offer radiators the ability to passively control heat rejection. In previous efforts, the first ever morphing radiator prototype was constructed and tested in a thermal vacuum environment, where it successfully demonstrated the morphing behavior and variable heat rejection. Newer prototypes incorporating highly thermally conductive composite materials have more recently been designed and manufactured using two distinct types of SMA materials. The design process is complicated by the contradictory requirements of good radiator performance, which is associated with stiff, brittle materials and thick panels, and good morphing performance, which requires compliant structures. The successfully designed models underwent temperature cycling tests in a thermal vacuum chamber and a series of fatigue tests to characterize the lifespan of these designs. A summary of these experiments and their results is provided while ongoing and future efforts are described.

10164-91, Session PMon

Magnetically-levitated nonlinear energy harvester: non-dimensional analysis and enhancement techniques

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Current nonlinear magnetic levitation-based approaches encapsulate several design challenges. For example, a traditional magnetic levitation-based energy harvester may use a displacement rod or a guiding rail to prevent the levitated magnet from flipping and realigning itself with the stationary magnet. Work presented here is focused on quantifying and evaluating major obstacles and challenges facing traditional designs. In addition, enhancement techniques are introduced and investigated using non-dimensional model. To achieve the goal of this work, both model and experiment are used. Results show that dry friction, mostly ignored in literature of magnetic levitation-based energy harvesting, contributes to energy dissipation and may affect the dynamic behavior of energy harvester. Measured and modeled magnetic forces-displacement curves suggest that stiffness nonlinearities are weak over moderate displacements. To overcome some of those limitations an enhanced design that uses a combination of magnetic and oblique mechanical springs is introduced. Non-dimensional model is developed to investigate the proposed design. Results show that proposed design results in additional nonlinearities which may contribute to the broadband operation of the energy harvester.

10164-92, Session PMon

Global stabilization control of high-energy responses of a nonlinear wideband piezoelectric vibration energy harvester using a self-excitation circuit

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This paper presents a resonance-type vibration energy harvester using a Duffing-type nonlinear oscillator with a self-excitation circuit. The bandwidth of the resonance peak and the performance of the power generation at the resonance frequency are trade-off for the conventional linear vibration energy harvester. A Duffing-type nonlinear oscillator can expand the resonance frequency band to generate lager electric power in a wider frequency range. However, it is difficult for the nonlinear wideband vibration energy harvester to maintain the highest-energy solution constantly since the nonlinear oscillator can have multiple stable steady-state solutions in the resonance band. In order to provide the global stability to the highest-energy response, we introduce a self-excitation circuit which can destabilize other unexpected lower-energy solutions and entrain the oscillator only in the highest-energy solution. This circuit consists of the load circuit and the positive velocity feedback circuit (PVFC) and has a switching control between two circuits depending on displacement amplitude of the nonlinear oscillator. PVFC can send voltage relative to velocity of the nonlinear oscillator to piezoelectric elements. Theoretical and numerical analyses show that the proposed self-excitation control can provide the global stability to the highest-solution and maintain the performance of the power generation at the resonance frequency.

10164-93, Session PMon

A tri-input energy harvesting system using thermoelectric generator, electromagnetic, and piezoelectric

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Over the last two decades of development by researchers and industry, energy harvesting systems has taken a great attention while consumption of electronic systems decreases. Energy harvesting systems have started to replace batteries in remotely controlled applications. Considering long term operations, it reduces the expenses of battery replacement. Studies in energy harvesting techniques show by utilizing multiple sources in harvesters, the total harvested energy increases and more practical, counting the loss in the power conditioning process. Such system requires complex algorithm and advanced control techniques. In spite of energy sources complexity, it requires stable outcomes as well as high

efficiency power converters. In this paper, by combining thermoelectric, electromagnetic, and piezoelectric, the harvesters source power in order of tens of miliwatts. Low temperature difference is considered for thermoelectric energy harvester. Low power electromagnetic harvester and piezoelectric are implemented at their resonant frequencies. The first stage of harvester utilizes either maximum power point tracking (MPPT) or impedance matching techniques to each sources. The second stage is designed to have two different output voltages available to supply two different applications simultaneously. For instance, the harvesters can supply two independent sensors in the same environment. A transformer converts three inputs into two and analog voltage feedback control watches the instantaneous output voltages through loads and available battery voltage. Rechargeable battery serves as a backup source in the event of energy shortage. Excess harvested energy not used by both loads is utilized to recharged the battery. Current feedback control monitors available sources to make sure when to operate the battery on time. These feedback control systems decided when to enable or disable the operating switches in the whole system.

10164-94, Session PMon

Impedance modeling of electromagnetic energy harvesting system using full-wave bridge rectifier

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Electromagnetic (EM) induction has been utilized for long as one of the most important electromechanical transduction mechanisms. Its principle can be used for constructing the EM energy harvesting (EMEH) systems, which scavenges the electrical energy from the ambient vibration. In an EMEH system, the generated AC electrical power is converted into DC by a rectifier, e.g., the full-wave bridge rectifier, which is nonlinear in nature. The influence of the power rectification towards the vibrational dynamics is of concern. Yet, conventional model of general energy harvesters [1], [2], as shown in Figure 1(a), regards the harvesting effect as the electrical induced damping. By taking this simplification, many detailed dynamic behavior produced by practical power conditioning circuits have been overlooked.

This paper presents an improved impedance model for the EMEH system considering the detailed dynamic components brought in by the most extensively used practical AC-to-DC interface circuit, the full-wave bridge rectifier. The operations of the power electronics under (current) continuous-conduction mode (CCM) and discontinuous-conduction mode (DCM) are studied under harmonic excitation. The waveforms, energy cycles, and impedance pictures are illustrated for showing more information about the working principle, energy flow, and dynamic details of the EMEH system. The results explain that the effect of the electrical part of an EMEH system (the self-inductance of the EM coil in series with the power conditioning circuit) can be equivalently modeled as three correlated dynamic components: the additional stiffness K_E, the dissipation components R_d, and the harvesting components R_h, whose values are functions of the rectified voltage in the bridge rectifier, as shown in Figure 1(b).

Moreover, since the first-mode coupling equations of the magnetostrictive energy harvester are the same as those of the electromagnetic case, this impedance model can also be used for the study of magnetostrictive energy harvesting. Since the impedance model of the piezoelectric energy harvesting (PEH) system is already known, the transduction mechanisms and impedance model of the EMEH and PEH systems, as shown in Table I, are also comparatively studied towards better understanding about the vibration energy harvesting systems.

10164-95, Session PMon

Design and experimental study of a velocity amplified electromagnetic vibration energy harvester

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Energy harvesting from vibration has been widely studied, however, a significant problem remains in which small vibration amplitudes are difficult to fully utilize. It is particularly important in environments where vibrating machinery, infrastructure, and fluid flow systems should be monitored for potential issues relating to structural health. This form of powered monitoring can be especially cumbersome in nuclear, and other large, power plants where batteries and many long cables may fail due to extreme conditions, and are expensive to install and maintain. Harvesting energy from the vibrating machinery or structures themselves using piezoelectric or electromagnetic transducers is a promising alternative which can locally power both the sensor, and wirelessly transmitting data nodes. Difficulty, however, remains in finding a solution for extracting useful power from low amplitude vibrational machinery. This current project aims to develop a solution which can increase power output from electromagnetic generators by increasing velocity. A novel new velocity amplification frame has been developed along with a specifically designed electromagnetic generator to be used within the spring steel frame. The frame utilizes both geometry and flexure segments to increase the amplitude and relative velocity between the coil and magnet generator by ~5.6x, and produces mW level power.

10164-96, Session PMon

Scavenging energy from human limb motions

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Scavenging energy from human motions via piezoelectric effect has received extensive research interests recently as it can achieve energy autonomy for portable and wearable devices. Human motions involve diverse mechanical movements providing accelerations with different frequencies. Conventional piezoelectric energy harvesters (PEHs) can only scavenge energy from excitations with a specific frequency. This deficiency severely limits the performance of PEHs in energy scavenging from human motions, especially the motions of limbs. This paper proposes a two-stage PEH to tackle this problem. The proposed PEH is composed of a ferromagnetic ball and a sleeve sandwiched between two piezoelectric cantilever beams. The piezoelectric beams, which are sensitive to excitation along the radialis or tibial axis, generate electrical outputs. The ball is employed to sense the swing motions of human limbs and travels along the sleeve to excite the beams. Theoretical and experimental studies are carried out to examine the performance of the proposed PEH when it is fixed at the wrist, ankle and thigh of a male when traveling at constant velocities of 2 km/h, 4 km/h, 6 km/h, and 8 km/h on a treadmill. The results indicate that the ultra-low frequencies of human motions are up-converted. During each step, the ball can trigger each beam at least twice, superposed with the acceleration along the radialis or tibial axis, to produce multiple peaks in the voltage output. Moreover, the voltage output of the PEH increases when the walking speed ranges from 2 km/h to 8 km/h.

10164-97, Session PMon

Impedance analysis of piezoelectric energy harvesting system using synchronized charge extraction interface circuit

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Piezoelectric materials, as a kind of the important and extensively used electromechanical transducers, can be used to converter mechanical kinetic energy into electrical. The dynamics and harvested power of piezoelectric energy harvesting (PEH) systems differ when different interface circuit is connected. The synchronized charge extraction (SCE) interface circuit is one of the popularly utilized circuits for PEH enhancement. It is unique for the advantage that, ideally, its output power is independent of the load. Most literature about SCE is based on the ideal conditions such as lossless diodes in the rectifier, ideal energy transfer in every switching instant. The actual energy details and electrically induced dynamics were somehow oversimplified.

This paper provides an impedance analysis on the PEH system using SCE interface circuit towards a more comprehensive understanding on its dynamics and harvested power. It starts from analyzing the equivalent impedance of the electrical part according to the voltage and current waveforms. Through qualitative analysis on the energy cycle, which is shown in Figure 1, we find that the electrically induced dynamics in the PEH system with SCE is contributed by three components: the accompanied capacitance Ca, dissipative resistance Rd, and harvesting resistance Rh, which correspond to an additional stiffness, dissipative damping, and regenerative damping in the mechanical domain. Considering the practical circuit conditions, quantitative result shows that the values of these components in not fully independent of the load resistance, or equivalently, the output DC voltage. Maximum harvested power point also exists in SCE as in other interface circuits. The changing rate of the harvested power on output DC voltage is studied in details. Experiments on practical PEH systems show good agreement with the analytical results.

SCE is somehow regarded as the most practical PEH interface circuit by some researchers, because of its exempt of maximum power point tracking stage towards simple and efficient design. By comparing SCE to other interface circuits including the bridge rectifier standard energy harvesting (SEH) and parallel- and series- synchronized switch harvesting on inductor (P- and S-SSHI), in terms of harvested power, the strengths and weaknesses of practical SCE circuit are discussed more comprehensively in this paper.

10164-98, Session PMon

An energy harvesting system utilizing wind pressure fluctuations on building envelope

Jae-Chan Park, In-Ho Kim, KAIST (Korea, Republic of); Seon-Jun Jang, Hoseo Univ. (Korea, Republic of); Hyung-Jo Jung, KAIST (Korea, Republic of)

This paper investigates a new energy harvesting system utilizing wind pressure fluctuations acting on building envelope, which is an unused and unavailable area for harnessing renewable energy in urban space. First, a series of wind tunnel tests with scaled building models and computational fluid dynamics (CFD) analyses are performed to examine the wind environments including wind pressure acting on a building and its fluctuation component. And then, an optimal structure and configuration of the energy harvesting system are devised based on the wind tunnel test and CFD simulation results, and its prototype is produced. Finally, the performance of the proposed energy harvesting system is numerically and experimentally validated.

10164-99, Session PMon

Bandwidth improvement by a novel piece-wise generator design with extended nonlinearities

Weiqun Liu, Congzhi Liu, Bingyu Ren, Qiao Zhu, Guangdi Hu, Southwest Jiaotong Univ. (China)

Incorporating nonlinearities into the structures is extensively studied as an effective approach to increase the operation band of the vibration generators. The piece-wise generator presents a simple realization of nonlinearities with good robustness since no magnetic interaction or pre-stress effect exists. However, the available nonlinearities are limited to the combination of two linear segments of stiffness, which hinders the performance of the harvesting device. In this paper, new piece-wise generator architecture is proposed with more possible nonlinearities realization while keeping the advantages of simplicity and robustness.

This EPW (Extended Piece-Wise) Generator utilizes a prolonged curve fixture instead of the stopper configuration of the RPW (Regular Piece-Wise) one. At the beginning, it behaves like a linear cantilever below the contacting threshold. Once above this value, the beam effective length is suddenly shortened and then slowly varies along the fixture as the load increases. Consequently, the stiffness nonlinearity relying on the chose curve is constructed.

Experimental displacement and power responses are presented with the theoretical responses of the equivalent RPW generator. The results show that the EPW generator possesses much better performance than the RPW generator with bandwidth enhanced effectively and resembled peak power. Good agreement between theory and experiment validates the model. By specifically choosing the curve of arbitrary type, continued or discontinued, we can find the desired design with better performance. More importantly, it shows good compatibility with the MEMS technology which facilitates the design, fabrication and assembling.

10164-100, Session PMon

A low-frequency vibration energy harvester based on diamagnetic levitation

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This article presents three-dimensional theoretical modeling, analysis, and experimental verification of a diamagnetically levitated vibration system with extremely low resonance frequencies for the use of vibration energy harvesting, pursuing further improvement of the earlier works by Palagummi et al., in terms of the size efficiency and the operation frequency. One of the key issues in the design of the diamagnetic levitation-based vibration energy harvester is the topology of the levitation system. In the proposed design, the levitation system consists of two permanent magnets, i.e., a floating magnet and a lifting magnet, and two diamagnetic plates parallel placed. The system is designed so that the floating magnet is stably levitated between the diamagnetic plates, and the primary vibration axis of the levitation system is taken horizontally. Thanks to the proposed new topology, this levitation system allows large vibration stroke for rather compact design. A proof-of-concept prototype of the proposed levitation system is designed, and the mathematical model of it is developed. We adopt the magnetic dipole model for modeling the attractive force between the floating and lifting magnets, and the thin coil model and the discrete volume method for he diamagnetic repulsive force comes from two diamagnetic plates. Then, the multi-degree-of-freedom equations of motion of the floating magnet are derived, and a three-dimensional motion analysis and its experimental verification are presented.

10164-101, Session PMon

Tunable thermo-triboelectric energy harvesting for human body heat applications

Dong-Gun Lee, Kwang-Yeop Jang, Korea Polytechnic Univ. (Korea, Republic of); James Lee, Seoul International School (Korea, Republic of)

We demonstrate a tunable thermo-triboelectric energy harvesting system for the use of human body heat as an energy source. There is a critical need for capabilities that will enable wearable electronics to incorporate self-thermal power from human body heat to solve challenges associated with battery issues such as limited life and recent exploding batteries fears. The widespread use of traditional bulk thermoelectric power generators (Peltier TEG) is currently limited due to low efficiency when exposed to very small temperature gradient between human body and environment. Magneto-Thermoelectric Generator platforms have great potential to provide new approach for thermal energy harvesting. The concept of MTG stems from a radically different technology developed by UCLA/KPU research community for harvesting of thermal energy. The proposed approach can convert thermal energy from human body heat into electricity by pairing triboelectric effect and MTG concept. The focus of this research is to determine the technical feasibility of presented technology platform for the consistent and efficient power performance using low temperature gradient from human body heat, including experimental characterization of a prototype fabricated.

10164-102, Session PMon

Development of flow control system for the reduction of vibration on wind turbine blades

Ho-Young Kim, Ho-Hyun Kim, Jong-Seob Han, Jae-Hung Han, KAIST (Korea, Republic of)

The size of wind turbine blade has been increased over the past few decades. As the wind turbine grows in size, generated noise and maintenance cost are also increased; it causes the eventual increases of the cost of energy. To reduce the noise and the cost of energy, wind turbine vibration has to be controlled. The vibration is caused by a blade rotation, tower shadow, wind shear, and flow separation on a wind turbine blade. Among them, the flow separation is one of the main reasons of generating vortex-induced vibration and decreasing the efficiency of wind turbine. In this paper, flow separation control for reducing the vibration is studied. The NREL 5MW wind turbine in typical operating condition is simulated to obtain the flow behavior. The active flow control device and MEMS-based flow separation detect sensor are developed in order to reduce the vibration and to increase the efficiency. Control strategies for reducing both vibration and energy consumption are proposed.

10164-103, Session PMon

Active vibration control for a smart panel with enhanced acoustic performances

Francesco Ripamonti, Manuel Molgora, Politecnico di Milano (Italy)

The spread of lightweight materials, such as composite panels and sandwich structures, recorded a significant increase during the last decades. These solutions, initially applied in aerospace, are now used in various fields such as automotive, civil construction,...

In addition to the extreme lightness, for equal stiffness, they are unfortunately characterized by a generally low damping, which affects their vibration behavior. This also results in reduced performance from an acoustic point of view, with particularly high indexes of reflection and transmission.

The aim of this work is to present an innovative smart plate able to modify its dynamic properties through the application of piezoelectric sensors and actuators. A numerical model of the plate has been developed with a FEM approach. An investigation about the system response in the high frequency range allowed to assess the acoustic behavior in terms of absorption and reflection coefficients. Then a suitable control logic has been studied in order to improve the acoustic performances. The system controllability and observability have been also analyzed, defining the best sensors and actuators layout for the proposed control logic.

10164-104, Session PMon

A highly flexible piezoelectret-fiber pressure sensor based on highly aligned P(VDF-TrFE) electrospun fibers

Jun-Yi Ke, Hsin-Jung Chu, Yu-Hsiang Hsu, Chih-Kung Lee, National Taiwan Univ. (Taiwan)

P(VDF-TrFE) is a ferroelectric material having a strong piezoelectric effect, a good chemical stability, chemical resistance and biocompatibility. Therefore, it is suitable for the development of flexible pressure sensors in biological applications. Using electrospinning process and a drum collector, P(VDF-TrFE) nanofibers are aligned and formed an ultrathin film sheet with a thickness of 15μm. A 140 °C annealing process and a corona discharge poling process are conducted to increase the performance of ? phase piezoelectricity. Based on this technology, a highly flexible piezoelectric pressure sensor is developed for measuring muscle movement on the surface of human body. The orientation of electrospun P(VDF-TrFE) fibers and poling direction will be studied to enhance the sensitivity of the piezoelectric-fiber pressure sensor. Preliminary study shows that sensitivity of piezoelectret-fiber pressure sensor can be 0.2512V/Pa after above processes with a high signal to noise ratios. Detail sensor design, experimental studies, and biological application will be detailed in this paper.

10164-105, Session PMon

Dynamics of periodic spring-mass chain coupled with an electric transmission line

Edoardo Belloni, Mattia Cenedese, Francesco Braghin, Politecnico di Milano (Italy)

Periodic structures have received large interest due to their peculiar behaviour: they have bandgaps, that is portions of the frequency response along with any wave incoming in the structure is reflected. Numerous are the applications, like metamaterials and locally resonant structures. Nowadays, new possibilities could come from mechanical periodic structures that are connected to an electrical transmission line, periodic in turn. Starting from this idea, this paper analyses ideal mono- and di-atomic spring-mass chains, considering the springs connected to a periodic electric network, composed by inductances (and resistors). Using the transfer matrix approach, these simple examples will show how the frequency response is affected. In particular, the mutual influence between the electric and mechanical domain is highlighted, and the contribution of parameters on bandgap positioning and design is explored. Details are provided about vibration modes and wave transmission.

10164-107, Session PMon

Low frequency control strategy for seismic attenuators with inertial monolithic mechanical sensors

Fabrizio Barone, Gerardo Giordano, Fausto Acernese, Rocco Romano, Univ. degli Studi di Salerno (Italy)

In this paper we present preliminary experimental results relative to the control of multistage seismic attenuators and inertial platforms in the band 0.01±10Hz, using open loop monolithic folded pendulums as inertial sensors.

In fact, beyond the obvious compactness and robustness of monolithic implementations of folded pendulums, the main advantages of this class of sensors are the tunability of their resonance frequency and their high sensitivity over a large measurement band. The results are presented and discussed in this paper together with the planned further developments and improvements.

10164-108, Session PMon

Implementation of a passive/active pendulum vibration absorber in a building-like structure

Diego Armando Flores Sanchez, Luis Alberto Zamora Campos, Univ. Politécnica de Pachuca (Mexico); Hugo F. Abundis-Fong, Univ. de Istmo (Mexico); Gerardo Silva-Navarro, Ctr. de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Mexico); Josué Enríquez-Zárate, RTO Energy (Mexico)

A passive and active vibration absorption scheme for a linear mechanical system subject to exogenous frequency harmonic excitation is proposed. The primary system is a story building-like structure, it consists of two rigid floors, connected by flexible columns with equivalent stiffness. The passive attenuation of the dynamic response of the primary system is obtained using a pendulum-type vibration absorber configured to work as Tuned-Mass-Damper collocated over the second floor of the structure. In order to improve the overall system performance against variations on the excitation frequency in the external force or possible parameter uncertainty, it is incorporated a servomechanism to modify the pendulum length and, therefore, the vibration absorber can be automatically tuned, by means of the application of a suitable control law. Some experimental and simulations results are included to show the dynamic behavior of the overall system.

10164-109, Session PMon

Semi active tunable mass damper for vibration suppression in helycopters

Simone Cinquemani, Francesco Braghin, Ferruccio Resta, Politecnico di Milano (Italy)

Helicopters are among the most complex machines ever made. While ensuring high performance from the aeronautical point of view, they are not very comfortable due to vibration mainly created by the main rotor. Traditionally this problem is solved by mounting several TMD inside the helicopter, each tuned to the frequency of the disturbance the main associated with the main rotor. In particular, this frequency is equal to the angular speed of the main rotor times the number of blades. Despite the angular speed of the main rotor is kept fixed and constant during the flight, it happens that some changes may be needed in particular situations.

Therefore it happens that the mass dampers are no more tuned and thus ineffective. This leads to a significant increase of the amplitude of vibration.

This work proposes to replace the purely passive systems with semi-active systems that are able to change their own natural frequency in order to be effective at each angular speed of the main rotor.

The paper deals with the preliminary analysis of the project to numerically and experimentally evaluate the feasibility of this solution

10164-110, Session PMon

Moving toward low frequencies active vibration control with inertial actuators

Simone Cinquemani, Andrea Costa, Ferruccio Resta, Politecnico di Milano (Italy)

In applications of vibration suppression, control forces ideally act on the structure increasing its damping. While the frequency response of the structure is guaranteed to have a positive real part under ideal conditions, in practice a stability limit exists when inertial actuators are used.

In this case the system response is no longer guaranteed to be positive real and so the control system may become unstable at high gains. Moreover, traditional approaches suggest the use of inertial actuators only if its natural frequency is well below the natural frequency of the structure, thus preventing their use at low frequencies.

This paper proposes an interesting technique to enlarge the operational range to lower frequencies and to allow the use of inertial actuators.

The approach is numerically tested and experimentally validated on a test rig.

10164-111, Session PMon

A novel tuned liquid concrete wall damper for multi-hazard mitigation

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Conventional gravity structural walls such as load bearing walls are designed to resist vertical loads only, and are assumed as inactive in the mitigation of lateral loads. We propose a novel multifunctional reinforced concrete wall panel system integrated with multiple-capillaries containing controllable fluids, which can act as both a load carrying member and semi-active Tuned Liquid Wall Damper (TLWD). The damping force of the proposed system is provided by the head loss of the fluid between each capillary, which can be controlled by mechanical valves at the connections between the capillaries and bottom pipe. In this paper, we experimentally demonstrate the damping capability of a prototype wall panel by subjecting it to different ground motions generated by a shaking table. The dynamic behavior will also be characterized by an analytical model.

10164-112, Session PMon

Light-induced and sensing capabilities of SI-ATRP modified graphene oxide particles in elastomeric matrix

Josef Osicka, Martin Cvek, Miroslav Mrlik, Tomas Bata Univ. of Zlin (Czech Republic); Marketa Ilcikova, Polymer Institute SAS (Slovakia); Vladimir Pavlinek, Tomas Bata Univ. of Zlin (Czech Republic); Jaroslav Mosnácek, Polymer Institute SAS (Slovakia)

Photoactuators can concern light stimuli in appropriate wavelength into mechanical response. Such reversible changes in the material shape are highly promising in their applications as remote controllers, or safety sensors. In this work we were focused on light-induced actuation and sensing performance of the prepared materials. In this case poly(dimethyl siloxane) PDMS with various amounts of silicone oil and curing agent was used as matrix. Graphene oxide (GO) as filler in its neat form as well as its modified analogues were used in several amounts (0.1; 0.5; 1 and 5 v/v%). Modified GO particles were controllably coated with silane-based polymer chains using surface-initiated atom transfer radical polymerization (SI-ATRP) approach in order improve interactions between the filler and matrix which consequently lead to the enhanced light-induced actuation performance. Generally the both, GO particles as well as modified ones were characterized using FTIR, Thermogravimetry, Raman spectroscopy and finally conductivity measurement to confirm the controllable coating and simultaneously proceeded reduction. By studying of dielectric properties (activation energies), melt rheology and viscoelastic properties which were investigated using dynamic mechanical analysis, the interactions between the filler and matrix were evaluated with connection to their light-responsive and sensing capabilities.

10164-113, Session PMon

Fabrication and design of novel self-biasing SMA sheet actuator

Nima Zamani, SmarterAlloys Inc. & University of Waterloo (Canada); Mohammad Ibraheem Khan, Smarter Alloys (Canada); Mir Behrad Khamesee, Univ. of Waterloo (Canada)

It was recently discovered that the material composition, and thermomechanical properties, of NiTi shape memory alloys (SMA) can be locally modified by the process of Nickel evaporation during laser pulsing. The application of this technology on SMA sheets enables the possibility of different locations to have different properties. The unique behaviour of SMAs are caused by solid-state phase transformation between martensite and austenite. Mostly, the thermomechanical properties of SMAs fall into two main categories: shape memory effect (SME) which is a thermally induced phase transformation or Pseudo-elasticity (PE) which is a stress induced phase transformation. During SME, SMA undergoes a phase transformation from deformed martensite to austenite. During this processes the original shape of SMA is recovered from the deformed one. In order to this cycle to continue for actuation applications, the material has to be deformed at every cycle in its martensite state. This is typically achieved by using some external force such as spring or a constant weight.

In the proposed actuator design, the deformation force (also known as biasing force) is applied by the PE portion of the actuator to its laser processed SME potion. PE portion acts as a biasing spring, and SME portion acts as the actuator. This enables cyclical a reliable two-way actuation without the need of external mechanism which affects the fatigue life of the actuator negatively. Subsequently, the final desired shape is cut from the laser pulsed NiTi sheet. This technique results in an actuator which has a different geometry and material composition on the sheets.

10164-114, Session PMon

Design and analysis of hybrid morphing smart wing

Chetan Gupta, Ramesh Gupta, The Shiv Nadar Univ. (India)

Unmanned aerial vehicles, of all sizes, are prime targets of the wing morphing concept as their lightweight structures demand high aerodynamic stability while traversing unsteady atmospheric conditions. In this research study, a hybrid morphing technology is developed to aid the trailing edge of the aircraft wing to alter its camber as a monolithic element rather than functioning as conventional appendages like flaps. Kinematic tailoring, actuation techniques involving shape memory alloys(SMA), piezoelectrics – individually fall short of providing a simplistic solution to the conundrum of morphing aircraft wings. On the other hand, the feature of negligible hysteresis while actuating using compliant mechanisms has shown higher levels of applicability and deliverability in morphing wings of even large aircrafts. This research paper delves into designing a wing section model with a periodic, multi-stable compliant structure requiring lower orders of topological optimization. The design is sub-divided into three smaller domains with external hyperelastic connections to achieve deflections ranging from -15° to +15° at the trailing edge of the wing. To facilitate this functioning, a hybrid actuation system by combining the larger bandwidth feature of piezoelectric macro-fibre composites and relatively higher work densities of shape memory alloy wires are used. Finite element analysis is applied to optimize piezoelectric actuation of the internal compliant structure. A coupled fluid-surface interaction analysis is conducted on the wing section during morphing to study the development of the velocity boundary layer at low Reynold's numbers of airflow.

10164-115, Session PMon

A smart-damper in vertical secondary suspension for the comfort increase in passenger trains

Francesco Ripamonti, Andrea Chiarabaglio, Ferruccio Resta, Politecnico di Milano (Italy)

Passive oil dampers are characterized by an equivalent damping coefficient, which depends on the speed of excitation, and an equivalent stiffness coefficient, which increases with the excitation frequency. This behavior is not acceptable for many high-performance applications. For example, in order to increase passenger train comfort and to improve handling, a mechatronic approach able to modify the design of the dampers of the carbody secondary suspension, represents a very attractive solution. In particular, semi-active dampers offer many advantages with respect to standard passive solutions. Indeed, the damping coefficient can be continuously adjusted according to the application requirements.

In this paper, a control strategy for semi-active damper is presented. This control logic allows to select the desired damping as function of the excitation frequency independently from the amplitude, i.e. from the excitation speed. Once imposed a threshold frequency, it is possible to modify both equivalent damping and stiffness coefficients overcoming the undesired effects of passive oil dampers. In order to assess the performance of the proposed control logic, the behavior of a train vertical secondary suspension is simulated. The controller aims at assuring the maximum available damping around the first rigid eigenmode of the carbody (at low frequency), while the desired equivalent damping and stiffness coefficients are set to zero at higher frequency, minimizing the force transmitted to the carbody able to excite the bending modes at higher frequency.

10164-116, Session PMon

Optimization of a two-frequency-two-mode traveling-wave piezoelectric linear motor by electrode design

Sheng-Hsun Wu, Chia-Chin Li, Tsun-Hsu Chen, Wen-Jong Wu, Chih-Kung Lee, Yu-Hsiang Hsu, National Taiwan Univ. (Taiwan)

Traveling wave type piezoelectric motor can be classified into linear and rotary types. Among them, a linear motor has an inevitable problem since finite boundaries are always exist, and reflected waves can hinder the formation of propagating waves. To solve this problem, a linear motor based on a single driving frequency and two induced resonant molds was previous reported. However, the driving frequency was not at structure resonant frequency, the efficiency of linear motor was limited. In this paper, we will introduce a new type of linear motor, it is based on the superposition of two adjoining bending modes called two-frequency-two-mode excitation. A traveling wave is created by two piezoelectric actuators driven by two different resonant frequencies. The location and size of the two piezoelectric actuators are studied to optimize the performance of the linear motor. Based on preliminary study, it suggested that by placing these two actuators at 51.7 mm and 128.8 mm with a length of 21.3 mm on a 180 mm on-dimensional beam could have the optimal performance. It will be demonstrated that a propagating wave can be created by using temporal phase difference in two driving signals and spatial phased difference on actuator placement, and the driving efficiency can be much improved through operating at two resonant modes.

10164-117, Session PMon

Active vibration suppression of helycopter horizontal stabilizers

Simone Cinquemani, Gabriele Cazzulani, Ferruccio Resta, Politecnico di Milano (Italy)

Helicopters are among the most complex machines ever made. While ensuring high performance from the aeronautical point of view, they are not very comfortable due to vibration mainly created by the main rotor and by the interaction with the surrounding air. One of the most solicited structural elements of the vehicle are the horizontal stabilizers. These elements are particularly stressed because of their composite structure which, while guaranteeing lightness and strength, is characterized by a low damping.

This work makes a preliminary analysis on the dynamics of the structure and proposes different solutions to actively suppress vibration. Among them, the best in terms of the relationship between performance and weight / complexity of the system is that based on inertial actuators mounted on the inside of the horizontal stabilizers.

The work addresses the issue of the design of the device and its use in the stabilizer from both the numerical and the experimental points of view.

10164-118, Session PMon

Design and experimental verification of an improved magnetostrictive energy harvester

Maxim Germer, Uwe Marschner, TU Dresden (Germany); Alison B. Flatau, University of Maryland (United States)

This paper summarizes and extends the modeling state of the art of magnetostrictive energy harvesters with a focus on the pick-up coil design. The harvester is a one-sided clamped GalFeNOL unimorph loaded with two brass pieces each containing a permanent magnet to create a biased magnetic field. Measurements on different pick-up coils were conducted and compared with results from an analytic model. Resistance, mass and inductance was formulated and proved by the measurements. Both, the length for a constant number of turns and the number of turns for a constant coil length, were also modeled and varied. The results confirm that the output voltage depends on the coil length for a constant number of turns and is higher for smaller coils. In contrast to a uniform magnetic field, the maximal output voltage is gained if the coil is placed not directly at but near the fixation. Two effects explain this behavior: due to the permanent magnet next to the fixation, the magnetic force is higher and orientates the magnetic domains stronger. For that reason the material is stiffer and therefore the strain smaller. The tradeoff between a higher induced voltage in the coil and an increasing inductance and resistance for every additional turn are presented together with an experimentally validation of the models. Based on the results an optimal coil was designed which maximizes the output power for a given unimorph.

10164-34, Session 7

Longitudinal metastructure bar with an active vibration absorber

Katherine Reichl, Daniel J. Inman, Univ. of Michigan (United States)

This work addresses two issues in lightweight structural composites suitable for aerospace systems. The first is to add additional functionality to multifunctional composites and the second is to provide damping in structures that cover a wide range of frequencies and temperatures. Passive damping in all materials suffer from failing at certain temperature and in certain frequency ranges. The extreme environments often seen by aerospace structures provide high temperature, which is exactly where damping levels in structures reduce causing unacceptable vibrations. In addition, as loading frequencies decrease damping levels fall off, and many loads experienced by aerospace structures are low frequency. This work looks at the implementation of a control system to a longitudinal metastructure bar. A metastructure is a structure which has distributed vibration absorbers which provide passive damping to the system. The active control system will be implemented by adding piezoelectric materials to one of the absorbers to make the absorber active. The structure with the active vibration absorber will be compared to a structure of equal weight with no active components. Since the two comparison structures are of equal weight, the performance improvements are strictly due to the control system and not at the cost of additional weight.

10164-35, Session 7

Piezoelectric metamaterials with synthetic impedance shunts

Christopher Sugino, Georgia Institute of Technology (United States); Stephen M. Leadenham, Lawrence Livermore National Lab. (United States); Massimo Ruzzene, Alper Erturk, Georgia Institute of Technology (United States)

We present an electromechanical metamaterial beam based on a piezoelectric bimorph with segmented electrodes. The structural response is governed by a frequency-dependent stiffness term, which depends on a material/geometry-based electromechanical coupling parameter and the impedance of the shunt circuits. Methods for choosing the shunt circuit impedance based on the desired structural response are discussed, with an emphasis on vibration attenuation and practical design considerations. Care must be taken to choose enough electrodes for the frequency range of interest, but not so many that the piezoelectric capacitance of each pair of electrodes becomes too small. A piezoelectric bimorph beam was fabricated with segmented electrodes, and synthetic impedance circuits were used to provide flexibility in the impedance applied to each pair of electrodes. Electrode segmentation was achieved by chemically etching the nickel electrodes on off-the-shelf PZT-5A sheets using a toner-transfer procedure. Wire leads were included in the electrode design to allow for electrode access beyond the clamp of the bimorph. Experimental results are presented for a variety of circuit impedances along with the corresponding model predictions and conclusions are drawn.

10164-36, Session 7

Tunable acoustic metamaterial based on PZT

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Acoustic metamaterials have attracted considerable attention recently. These materials are of special interests because they can give rise to 'on-demand' effective properties, without the constraints imposed by what nature provides. In this paper, a metamaterial consisting of periodic layers of steel, polyurea and piezoelectric ceramic transducer (PZT) was presented. Note that the PZT layer in this structure was shunted by an inductor L. Transfer matrix method was used to calculate the band structure of the sample. It was observed that an extremely narrow stop band was induced by the PZT layer. This narrow stop band was attributed to the resonance circuit constituted by the piezoelectric layer, for the piezoelectric layer with electrodes could be seen as a capacitor. Further, homogenization method was used to calculate the effective elastic constants of the sample. Results showed that the effective elastic constant behaved negative in the narrow stop band. For the the location of this stop band was dependent on the PZT layer's resonant frequency, it could be easily tuned by changing the external connected inductance without changing the structure of the metamaterial. However, this type of stop band was extremely narrow which seriously limited its application. So influences of the width of stop band was investigated. And the way to expand this narrow stop band was in research. These results can be used to design design noise insulators, acoustic filters, as well as vibration insulators.

10164-37, Session 7

A metastable modular structural system for adaptive nonreciprocal wave propagation

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In this research, we present a novel approach to achieve adaptive nonreciprocal wave propagation by exploiting the concept of metastable modular metastructure. Numerical studies on a 1D metastable chain provide clear evidence that such nonconventional wave transmission characteristics is facilitated through both nonlinearity and spatial asymmetry of strategically configured constituents. Due to a synergistic product of assembling together metastable modules, modules that exhibit coexisting stable states for the same topology, recent investigations have demonstrated remarkable programmability of properties afforded via transitioning amongst these metastable states. In the context of wave transmission, such massive property adaptation provides unprecedented bandgap tuning opportunities and therefore enables the adaptivity of nonreciprocal wave propagation. In addition to metastable states, influence of wave amplitude and frequency on the existence and adaptation of nonreciprocal wave transmission is also parametrically explored. Overall, this investigation elucidates the rich dynamics achievable by nonlinearity and metastabilities, and creates a new class of adaptive structural and material systems capable of achieving tunable bandgaps and nonreciprocal wave transmissions.

10164-38, Session 7

Toward structurally integrated locally resonant metamaterials for vibration attenuation

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We explore the use of locally resonant metamaterials for multi-functional structural load-bearing concepts using analytical, numerical, and experimental techniques. Locally resonant metamaterials exhibit bandgaps at wavelengths much larger than the lattice dimension as a promising feature for low-frequency vibration attenuation. The present work aims to investigate highly integrated structural concepts and experimentally validated prototypes for vibration reduction in load-bearing applications. The goal is to explore and extend the design space of lightweight structural systems, by designing multi-functional periodic structural elements, preserving structural stiffness while concurrently enabling sufficiently wideband damping performance over a target frequency range of interest. Following a generalized theoretical modeling framework for bandgap design and analysis in finite structures, the focus is placed on the design, fabrication, and analysis of a load-carrying frame development with internally resonant components. Finite-element modeling is employed to design and analyze the frequency response of the frame and simplified analytical solution is compared with this numerical solution. Experimental validations are presented for a 3D-printed prototype. The effects of various parameters are reported both numerically and experimentally.

10164-39, Session 8

An earthworm-like robot using origami structures

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This study addresses the problem of developing earthworm-like robot with origami techniques. To this goal, we first determine the requirements that an origami structure needs to satisfy so as to behave like an earthworm body segment. Then a set of eligible crease patterns are identified, and numerical analysis and experiments are performed; we investigate and show that the corresponding folded structures are able to exhibit earthworm-like deformations, and thus can be employed for constructing robots. Among these origami designs, we focus on the origami ball pattern because the folded structure possesses exceptional characteristics including expanded design spaces, large deformations, increased stiffness, and structural bistability. Utilizing the origami ball as the robot segment framework and employing an active linkage actuated by servo motor, a proof-of-concept robot segment is developed, and a six segments earthworm-like robot is assembled. By applying a peristalsis gait control, the robot is able to perform effective locomotion inside a tube. The origami-based earthworm-like robot shows several advantages over conventional designs: the robot framework is developed from a plane sheet with extensive freedom; the laser-based fabrication and folding-based assembly is effective and precise; the obtained robot structure is of light weight but of high structural stiffness; and the robot framework possess structural bistability that can be employed to reduce actuation requirement.

10164-40, Session 8

Multistability inspired by the oblique, pennate architectures of skeletal muscle

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Skeletal muscle is a multifunctional system demonstrating significant robustness, versatility, and force adaptability, and provides great inspiration for the development of advanced structural and material systems. These characteristics arise from the synergies demonstrated between muscle's constituents across the various length scales. From the macroscale pennate orientation of muscle fibers to the microscale lattice spacing of sarcomeres, muscle takes advantage of geometries and multidimensionality for force generation or length change along a desired axis. Inspired by these behaviors, this research investigates how the incorporation of multidimensionality afforded by oblique, pennate architectures can uncover novel mechanics in structures exhibiting multistability. Experimental investigation of these mechanics is undertaken using samples of molded silicone rubber with patterned voids, and results reveal tailorable mono-, bi-, and multi-stability under axial displacements by modulation of transverse confinement. If the sample is considered as an architected material, these outcomes show its ability to generate intriguing, non-monotonic shear stresses. The outcomes would foster the development of novel, advanced mechanical metamaterials that exploit pennation and multidimensionality.

10164-41, Session 8

A micromachined ultrasonic power receiver for biomedical implants

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Bio-implantable medical devices need a reliable and stable source of power to perform effectively. Although batteries can be the first candidate to power implantable devices as they provide high energy density, they cannot supply power for long periods of time and they must be periodically replaced, which requires surgery. In this paper, we develop a micromachined ultrasonic power generating receiver with a size of less than 1cmx1cm capable of providing sufficient power for implantable medical devices. The ultrasound receiver takes the form of a unimorph diaphragm consisting of PZT on silicon. We dice bulk PZT with a thickness of 127 μm and bond the diced pieces to a silicon wafer. In order to get a 50 μm thick PZT layer, which is needed for optimal power transfer, we mechanically lap and polish the bonded PZT. We investigate the performance of the fabricated receiver both numerically and experimentally. The output displacement of the receiver is measured for different excitation voltages, and the output power of the receiver is measured when an ultrasound transmitter is placed at various distances from the receiver in water. The performance and efficiency of the whole system are discussed. We show that when the transmitter is generating an input power less than Food and Drug Administration limits, the receiver can provide sufficient power for many implantable devices. Furthermore, the process developed can be used to fabricate significantly smaller devices than the one characterized, which enables further miniaturization of bio-implanted systems.

10164-42, Session 8

Smart composites based on controllably grafted graphene oxide particles and elastomeric matrix with tunable sensing capability

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Stimuli-responsive materials attracting a lot of attention from both groups, academic and industrial environment, due to the several challenges (impact of the filler, matrix and material properties), since some of them were still not properly understood. Moreover, the reversible actuation upon external stimulus such as light is still very interesting in case of various applications (sensing or energy harvesting) This study utilize the simple fabrication method for graphene oxide (GO) particles preparation, their controllable modification using surface initiated atom transfer radical polymerization (SI-ATRP) tehcnique and thus suitable interaction with elastomeric matrix for final enhancement and controlling of the sensing capability upon light stimulus. GO particles were characterized by Fourier transform infrared spectroscopy, Thermogravimetric analysis and Raman spectroscopy to properly see the controllable coating as well as reduction of GO in the single-step synthesis. The composites containing various amounts of GO, controllably modified GO and elastomeric matrix poly(vinylidene-co-hexafluoropropylene) elastomer was characterized by dielectric spectroscopy, dynamic mechanical analysis and thermal conductivity. The phenomenon how the GO and modified GO particles influence the mobility of the polymer chains, thermal conductivity will be investigated. The impact on change of the material properties on the light-responsive and sensing capability will be discussed.

10164-43, Session 9

Nonlinear analysis of micro piezoelectric energy harvesters

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This talk presents an investigation of the nonlinear behavior of micro piezoelectric cantilever beams made of the PZT film deposited on the stainless-steel substrate. The nonlinearity is induced due to the heavy proof mass under amplified excitation. Our previous experiment found the frequency response of the energy harvester exhibited the hardening type of nonlinearity. The observed phenomenon was explained by proposing a framework considering both the geometric and inertia nonlinearities. However, the nonlinearity of softening type was recently found in different samples with relatively thick in film thickness. The explanation was not clear then. Here the consideration of material nonlinearity in the PZT layer due to amplified excitation is included for resolving this issue. The frequency response is determined by applying the method of multiple scale analysis to the reduced formulation under various magnitudes of excitation and electric loads. In particular, the coefficients of damping and material nonlinearity are estimated from the backbone curve fitted using the relevant experimental data. As a result, the nonlinearity of the softening type is predicted and is in good agreement with the experimental observations. Besides, for the samples with the smaller film thickness as in our previous case, the overall strength of material nonlinearity is weak, causing the frequency response of hardening type.

10164-44, Session 9

Maximizing direct current power delivery from bistable vibration energy harvesting beams subjected to realistic base excitations

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1 Introduction

Many of the monitored structures in structural health monitoring applications are in motion due to various excitation mechanisms [1]. Thus, a promising solution of recent interest is to harvest this ambient kinetic energy and convert it into electric power to sustain the functionality of sensor nodes that keep watch over the condition of the structure [2]. To this end, vibration energy harvesters are considered as the means to provide this power delivery [3]. Previous studies have shown that bistable structures are strongly sensitive to many ambient vibrations that serve to excite them, encouraging their consideration as energy harvesting platforms [4] [5] [6] [7]. Such performance is enabled by the large amplitude snap-through dynamics, so long as they are consistently maintained. However, bistable structures may exhibit coexistent dynamics under pure harmonic excitations, since for the same excitation the system may undergo a low amplitude intrawell oscillation state around one of the stable equilibria. This result greatly reduces the harvested power due to reduced energy conversion of the low amplitude "intrawell" state [8] [9]. In addition, ambient kinetic energies are time-variant unlike the harmonic excitations commonly considered in the study of nonlinear vibration energy harvesters [8]. The time variation may be realized by transient spectral content and/or random noise, which makes the dynamic response of bistable structures more complicated to assess [10]. Previous research has investigated the response of linear energy harvesters under harmonic excitation with time-varying

frequency [11], impulsive inputs [12], and band-limited noise [13]. Yet, the effectiveness of bistable energy harvesters that are subjected to more realistic excitations with combined harmonic and stochastic characteristics is insufficiently understood.

In addition, sensors require direct current (DC) power delivery [14]. Thus, a bistable harvester needs an AC-DC rectifier to interface between the oscillatory electromechanical response and the electrical load. While researchers have found that standard diode bridge rectifiers, synchronized switch harvesting on inductor circuits, and the synchronized electric charge extraction circuits [15] [16] [17] [18] enable promising DC power delivery for linear vibration energy harvesters subjected to harmonic excitation, the corresponding electromechanical coupling effects of such AC-DC interfaces have not yet been characterized for bistable energy harvesters when subjected to realistic vibration inputs.

To identify best design and deployment strategies for bistable energy harvesters to deliver DC power under realistic non-stationary and random ambient vibration spectra, this research undertakes coordinated computational and experimental efforts. The following sections briefly describe the bistable energy harvester platform under consideration, its model methodology, and representative results. Ongoing studies are compiling a comprehensive characterization of the influences of the combined harmonic and random excitations on the DC power delivery.

2 Bistable energy harvester platform and model

2.1 Bistable energy harvester platform

Figure 1 provides a photograph and schematic of the experimental system examined here. The bistable energy harvester platform is constructed by a ferromagnetic spring steel cantilever beam clamped at one end in a rigid aluminum mount with a pair of neodymium magnets positioned near the beam free tip [19]. The bistability of the structure is introduced by the magnet pair with position parameters and , which causes the spring steel beam tip to statically point to either one of two stable equilibria, as shown in Figure 1(b). Four piezoelectric PZT-5A patches are bonded on the beam, two on each side, close to the clamped end. External excitations are applied through an electrodynamic shaker to which the two aluminum mounts are affixed.

2.2 General model formulation of bistable energy harvester

For this bistable energy harvester platform, the piezoelectric patches bonded near the beam clamp convert the base-excited vibrations of the cantilever to AC electrical voltage. Yet, microelectronics often need DC voltage and power to function. Thus, an AC-DC rectifier constructed by a standard diode bridge, with a filtering capacitance interfaces between the energy harvester and an electrical load , as shown in Figure 1(b). The diode bridge is assumed to be perfect in the following computational study.

The governing equations of motion for this system are shown to be [20]

Eq (1)

where , , are the viscous damping, linear, and nonlinear stiffness, and the load parameter is related to the nonlinear influences of the magnets that induce buckling (i.e. when) [19].

The diode bridge AC-DC converter is connected to the energy harvester as shown in Figure 1. is the current flowing into the diode bridge circuit and is related to the DC voltage output by [21]

Eq (2)

The base acceleration excitation includes harmonic and stochastic components

Eq (3)

such that is a Gaussian white noise process with

and

and where is the standard deviation of the noise [22]. Considering the harmonic excitation component, is the magnitude and the angular frequency of excitation.

3 Computational assessment of the DC power delivery

To complement experiment results, direct numerical simulation of the governing equations (1,2) is carried out. In the simulation results presented here, the responses are determined by numerically integrating Eq. (1,2) with parameter values identified experimentally, Table 1, and using 16 randomly-selected initial conditions to uncover all possible response forms induced by the base acceleration excitation. The numerical simulations are conducted with a high tolerance fourth-order Runge Kutta method to ensure that the triggering points of the bridge rectifier are accurately captured.

4 Experimental methods

The absolute cantilever tip displacement is measured by a Micro Epsilon ILD-1700 laser, while a Micro Epsilon ILD-2300 laser measures the displacement of the electrodynamic shaker table, with a collocated accelerometer (PCB Piezotronics 333B40) that measures the shaker table acceleration in the same axis of motion. The piezoelectric patches bonded to the beam are connected in parallel with the combined voltage output delivered to a diode bridge circuit as shown in Figure 1(b). The diodes in the bridge (1N4148) convert the AC voltage to DC voltage . A combination of resistor and charging capacitor (10 [μF]) is chosen so that the time constant in all examinations is much longer than the natural period of the bistable structure, to ensure the output voltage is constant. The electrodynamic shaker (LabWorks ET-140) is driven by an amplifier using a controlled signal to provide constant-amplitude acceleration at all frequencies considered in the experiments. Slow swept sine excitations, 0.1 [Hz/s], are provided to drive the shaker. The additive white noise is controlled by prescribing the variance of an additive, normally-distributed time series of voltage that superimposes with harmonic voltage that drives the shaker.

5 Results and discussions

A preliminary characterization of the bistable energy harvesting beam is conducted for base excitations composed of only the harmonic component with amplitude =4.3 [m/s2] and various harmonic frequencies [Hz], thus the noise standard deviation is =0 [m/s2]. The range of frequencies selected for close examination is around the linear natural frequency of the symmetrically-bistable beam, around 35 [Hz]. Figure 2 presents the experimental measurements in the left column and corresponding computational results in the right column. The plots in the top row are the magnitudes of the beam tip response at the corresponding excitation frequency, computed from a Fast Fourier Transform of the short-time sampled measurements, while the bottom row shows the corresponding DC power across the resistive loads .

The important range encompassing the snap-through vibrations and high power delivery around and at frequencies lower than the linear natural frequency is accurately reproduced in the simulation when compared to the measurements. Considering the important characteristics of Figure 2, such as the DC power delivery dependence upon the mechanical response of the beam and the range of frequencies across which this power is provided, the computational approach is in good quantitative and qualitative agreement with the experiment. This encourages the ongoing, comprehensive computational and experimental characterization to be reported in the full paper submission. The following paragraphs establish insights from further experimentation conducted and closely examined to date.

Many ambient kinetic energies are neither harmonic nor purely stochastic [10], which encourages an honest evaluation of the effectiveness of a promising vibration energy harvesting concept when it is subjected to such more realistic excitation form than traditionally considered. Then, experiments are conducted where the white noise standard deviation is =8.0 [m/s2]. To appreciate the significance of this noise level with respect to the amplitude of the harmonic contribution =4.3 [m/s2], Figure 3 plots the base acceleration measurements with and without the noise. Because the peak-to-peak of the combined input form is considerably greater than the pure harmonic input, one may expect that the beam response and DC power delivery are likewise magnified to the benefit of energy harvesting objectives.

Figure 4(a,b) respectively present measurements of the displacement amplitude at the excitation frequency and the average DC power delivered to a 820 k? resistive load. When the additive white standard deviation is increased to =8.0 [m/s2], despite the large increase in peak-to-peak base acceleration that drives the bistable energy harvester (see Figure 3), the measurements in Figure 4(a) show that the displacement amplitudes at the underlying harmonic excitation frequency are greatly reduced at frequencies around the natural frequency 35 [Hz]. This results in a reduction in DC power delivery, Figure 4(b), primarily in the range of 30-40 [Hz] where a vigorous snap-through oscillation occurs in the absence of noise.

On the other hand, frequency domain results do not tell the whole story.

Figure 5 presents time domain measurements for portions of the data recording that correspond to the spectral lines indicated in Figure 4 by labels A and B. The displacement responses, Figure 5(a), and piezoelectric and charged voltages, Figure 5(b), occur at 34.75 [Hz]. At this frequency, the bistable harvester driven by the purely harmonic base acceleration may respond in one of two coexisting dynamic regimes, the intrawell and snap-through responses, which are characterized with significantly different average DC powers as shown in Figure 2(b). As shown in Figure 5(a), the beam undergoes a large amplitude, snap-through oscillation when only the harmonic contribution to the input acceleration is provided. This leads to an average DC power delivery of 48 μW. Yet, when the base acceleration is increased by virtue of the large, additive white noise, the average power is reduced at 34.75 [Hz], as shown in Figure 4(b). This is despite the fact that the beam snaps through with regularity as shown in Figure 5(a). As evident in Figure 5(a), the snap-through response does not occur in sequence with the harmonic excitation. Considering the impact of this aperiodicity on the power generation, Figure 5(b) shows a notably reduced charging voltage which results in the average DC power delivery to be about 8 μW as shown in Figure 4(b). These results show that the introduction of large noise to the base acceleration that drives a bistable energy harvester may have clearly non-intuitive outcomes: larger peak-to-peak accelerations do not correspond to greater DC power delivery on the mean after rectification of the AC piezoelectric voltage.

6 Ongoing efforts

The ongoing efforts of this research are consolidating a concrete understanding of the sensitivities of DC power delivery from bistable energy harvesters when subjected to realistic base excitations. Through extensive computational efforts and experimental undertakings, the ongoing discoveries, not reported here for brevity sake, are determining guidelines for maximizing DC power delivery. The verified model formulation is concurrently being leveraged in the development of an efficient analytical approach to directly characterize the response of such energy harvesters for establishing a toolbox of knowledge for design and deployment.

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10164-45, Session 9

Broadband energy harvesting using phononic crystal with multiple defects

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Recent research on phononic crystal-based energy harvesting has shown drastic enhancements of energy conversion efficiency. Phononic crystals (PnCs) are periodically engineered structures which exhibit extraordinary phenomena such as negative refraction and bandgap. Phononic bandgap refers to a certain range of frequencies within which elastic waves are prohibited from propagating through the PnC. When there is an isolated defect in the perfect PnCs, the elastic waves are trapped at the defect location due to the appearance of the narrow passband in the middle of the bandgap. Since this defect band is attributed to local resonance of the PnCs, highly dense energy can be scavenged in the vicinity of the defect. Although many investigations of the point/line defect modes in PnCs have been reported, however, only a few research has been made in the multiply defected PnCs design, especially for exploiting the broadband characteristic stemmed from the several defect bands. In this study, we thus propose a multiply defected PnC design capable of operating over wide frequency ranges for enhanced power generation. A local-resonance based bandgap structure is newly proposed. With the geometric design variables, sizing optimization is conducted as the bandgap maximization subjected to a target frequency. Since the defect bands vary with the location of the defects, topology optimization is formulated to find the optimum number and location of the defects for maximizing the trapped energy. Lastly, the output power of the single defected PnCs is computed for the purpose of comparison with that of the proposed design.

10164-46, Session 9

Performance metric comparison study for non-magnetic bi-stable energy harvesters

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Energy harvesting continues to receive extensive attention from the adaptive structures community owing to the potential to serve as an autonomous power source for microelectronic components [1, 2]. Amongst the different ambient energy sources, vibrations have been shown to be a ubiquitous and reliable source for of power for accomplishing the objective of self-sufficiency for a number of applications. In this respect, one of the most relevant applications for energy harvesters is to provide autonomous power for implantable medical devices [3, 4], which require efficient energy conversion from low frequency vibrational sources around the human body. Despite the progress shown by the numerous studies presented in literature, several challenges including low frequency conversion efficiency, scalability, and biocompatibility remain to be fully addressed to enable the realistic operation of harvesting devices. A particular mechanism with the potential to offer viable solutions for these specific challenges is the utilization of elastic multi-stability in structures. Elastically multi-stable structures result from a particular state of induced strains causing a preloading in the structures [5]. Therefore the phenomenon is driven by the kinematics of deformation—given by the induced strains—rendering multi-stability a geometrically scalable and material independent behaviour [6]. The rich dynamics exhibited by multi-stable structures have been proven to offer an efficient and robust mechanism for converting vibrational energy into electrical power [7, 8]. Furthermore, the specific characteristics of multi-stable structures allow for converting energy at very low structural frequencies [9]. However, most examples of such devices utilize magnets to generate the multi-stability behavior posing incompatibilities both for human implantation, due to biocompatibility and dangerous electromagnetic interactions (e.g. during MRI scans), and due to possible interference with the microelectronic devices to be powered. Classes of non-magnetic harvesters obtaining its multi-stable behavior from thermally induced stresses during manufacturing show great promise to address the scalability, bio- and electrical compatibility problems of suffered by elasto-magnetic counterparts [10]. The design of the dynamic behavior and the associated device geometry for multi-stable harvesters still require the establishment of specific metrics allowing for optimization. Several metrics for optimizing the performance of such devices have been suggested, however each is better suited for specific operational conditions. Thus the problem of designing multi-stable harvesters still deserves further investigation.

This study presents a comparison of the harvesting characteristics utilizing available performance metrics of non-magnetic multi-stable composite laminates. A simple resistive circuit is used for energy conversion, thus allowing the benchmarking to focus on the mechanical behavior of the device. The performance is investigated using the piezoelectric layer thickness and electrical resistance as parameters, whilst power output is used as the optimization objective. The performance of the harvester is investigated for different dynamical regimes, including intra- and inter-well oscillations. Different single- and multi-frequency metrics are obtained and compared using the performance metrics available in literature [11] to yield the optimal configuration of the harvester. The obtained preliminary results indicate that a specific piezoelectric layer thickness is found to render the best performance by most of the tested metrics. The apparent insensitivity of the multi-stable harvester response to the different utilized metrics indicate that the optimization of the geometry yields a satisfactory and robust performance for the different operational conditions for which each of the indicators has been developed. The herein presented results thus shed light into the hitherto unresolved issue calling for the establishment of appropriate design guidelines for nonlinear, and particularly for multi-stable, energy harvesting devices.

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10164-47, Session 9

Enhanced vibration energy harvesting from oil drilling based on the principle of stochastic resonance

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Many harvesters have been developed in the past to harvest energy from oil drilling. Yet most of these harvesters are linearly resonant harvesters the power output of which drops dramatically under random excitation. This poses a serious problem because a lot of vibrations that occur when drilling for oil are stochastic. In this paper, an efficient electromagnetic bistable energy harvester using stochastic resonance is proposed to maximize power output when the excitation is random. Large power output can be produced with stochastic resonance by inputting a weak periodic signal(which frequency is matched to stochastic resonance frequency) and noise excitation into a bistable system. Buckled beam is used to induce bistability because it is more appropriate for oil drilling application than magnetic induced bistable mechanism. Theoretical modeling of harvester is also presented for design optimization. By using scaled prototypes, experimentation has disclosed the efficiency of stochastic resonance as an strategy for energy harvesting from oil drilling.

10164-48, Session 9

Performance evaluation of nonlinear energy harvesting with magnetically coupled dual beams

Chunbo Lan, The Univ. of Auckland (New Zealand) and Northwestern Polytechnical Univ. (China); Lihua Tang, The Univ. of Auckland (New Zealand); Weiyang Qin, Northwestern Polytechnical Univ. (China)

This paper proposes a nonlinear energy harvesting configuration with magnetically coupled dual beams. One beam is used for energy harvesting with piezoelectric component connected to a load resistance and the other for the introduction of an additional degree of freedom (DOF) and nonlinear dynamics. The performance of the proposed configuration is evaluated and compared with a traditional single DOF nonlinear energy harvester with magnetic coupling. First, the potential energy and stable equilibria of these two nonlinear energy harvesting configurations are investigated. Based on the analysis of stable equilibria, we determine four different nonlinearity regimes when the distance between repulsive magnets changes. Subsequently, nonlinear electromechanical models are established and the nonlinear responses of these two configurations are compared for each of the four nonlinearity regimes. The two systems are analysed and compared under various excitation levels. Results show that the magnetically coupled dual beam configuration is preferred only given a reasonable excitation level to ensure the vibrational energy to be easily transferred between the coupled dual beams. In such scenarios, dual beam configuration can achieve a wider bandwidth and provide a higher output power compared to the single DOF nonlinear energy harvesting configuration. When the excitation level is too low or too high, the vibration energy of the dual beams is not well transformed and thus the proposed dual beam configuration cannot guarantee a remarkable improvement in terms of bandwidth and magnitude of output power. Finally, the effect of load resistance on the proposed configuration is investigated.

10164-49, Session 9

Modeling of plucking piezoelectric energy harvesters with contact theory

Xinlei Fu, Wei-Hsin Liao, The Chinese Univ. of Hong Kong (Hong Kong, China)

Non-harmonic excitations are widely available in the environment of our daily life. We could make use of these excitations by plucking piezoelectric energy harvesters. Plucking piezoelectric energy harvesting could overcome the frequency gap and achieve frequency-up effect. However, there has not been a thorough analysis on plucking piezoelectric energy harvesting, especially with good understanding on the plucking mechanism. This paper is aimed to investigate the plucking mechanism and predict the responses of plucking piezoelectric energy harvesters under different kinds of excitations. In the electromechanical model, Hertzian contact theory is applied to account for the interaction between plectrum and piezoelectric beam. We postulate that plucking would be a special case of impact. A coefficient is defined to consider the influence of overlap length during plucking process. We analytically predict the plucking force, which depends on piezoelectric beam, Hertzian contact coefficient, overlap length and plucking velocity. We then compare the model prediction with experimental results in frequency domain. The model well predicts the responses of plucking piezoelectric energy harvester under low to medium plucking velocities. Parametric studies are conducted in order to provide guidelines for improving harvested energy under plucking excitations.

10164-50, Session 9

Experimental investigation of low aspect ratio, large amplitude, aeroelastic energy harvesting systems

Benjamin Kirschmeier, Matthew Bryant, North Carolina State Univ. (United States)

Recent interest in clean, stable, and renewable energy harvesting devices has increased dramatically with the volatility of petroleum markets. Specifically, research in aero/hydro kinetic devices has created a slate of new horizontal and vertical axis wind turbines, and oscillating wing turbines (OWTs). OWTs benefit from unsteady aerodynamic forces that can drive the oscillations to peak efficiency.

Small aspect ratio oscillating wings at low Reynolds numbers continue to be tested because of the complex flow structure they inherently present. A parametric experimental investigation was performed on a fully passive, low aspect ratio and Reynolds number, aeroelastic energy device with large amplitude oscillations to investigate the effects of various structural parameters on the performance of the device. The large amplitude motions, heave motions larger than 1 chord length peak to peak, and pitch rotations greater than 60 degrees, facilitate constructive unsteady aerodynamic effects that drive the system to higher efficiency.

10164-51, Session 9

Effective kinetic energy harvesting via structural instabilities

Ashkan Haji Hosseinloo, Konstantin Turitsyn, Massachusetts Institute of Technology (United States)

Vibration energy harvesting has been shown as a promising power source for many small-scale applications mainly because of the considerable reduction in the energy consumption of the electronics and scalability issues of the conventional batteries. However, conventional linear harvesters suffer from narrow frequency bandwidth and are inefficient for low-frequency excitation at small scales. Nonlinear harvesters, in particular bistable harvesters, are also not very robust to changes in excitation or system parameters. To remedy these issues, we propose to exploit structural instabilities, in particular instabilities in multi-layered composites or surface instabilities which are inherently non-resonant. Unlike conventional buckling instability where a compressively-loaded structure buckles into half wavelength shape, more interesting and complex morphological patterns e.g. wrinkle, crease, fold, and ridge arise when a multi-layered composite buckles. Large local strains are induced in these composite structures for two main reasons: i) once a critical stress is exceeded, the structure buckles resulting in lower overall structural stiffness which consequently leads to large macroscopic strain, ii) the nonlinear buckling pattern induces large local strains at specific periodic positions in the structure. The large induced strain could be exploited to harvest energy via piezoelectric patches. Here, we study energy harvesting from compressive loads via wrinkling in a multi-layered composite (stiff layers embedded within a soft matrix). Piezoelectric patches are attached to the stiffer interfacial layers at the peaks and troughs of the sinusoidal wrinkles. Results show that the induced voltage and hence, the harvested energy are significantly increased as a result of the wrinkling instability.

10164-52, Session 10A

Evaluation of human-scale motion energy harvesting for wearable electronics

Bharat Kathpalia, Ilan Stern, David Tan, Alper Erturk, Georgia Institute of Technology (United States)

The transformation of ambient mechanical energy into low-power electricity for enabling self-powered wireless electronic components has received growing attention over the last decade. Another growing field of research and industry is in the broad area of wearable electronics and sensors for a broad range of applications spanning from smart shoes that track sport performance to wristbands for fitness and health monitoring. At the intersection of these two emerging fields, we explore the potential of human-scale motion energy harvesting toward enabling self-powered wearable electronic components to avoid the burden of battery replacement and charging. To this end, in this paper, first we explore the motion intensity levels at select body parts (shoes, knees, wrists, etc.) with a focus on the acceleration (or force) and frequency content. Then various piezoelectric energy harvesting methods that employ bending and axial modes are evaluated and compared. The experimentally measured kinematic data is fed into our analytical electromechanical models for predicting the power output. Designed piezoelectric energy harvesters are also experimentally tested (under shaker excitation and during walking) for model validation and performance comparison. The overall potential of human motion energy harvesting using different piezoelectric energy harvesting modes is evaluated and conclusions are drawn.

10164-53, Session 10A

Energy harvesting from mouse click of robot finger using piezoelectrics

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Human motion is a good energy source for energy harvesting to support the power of wearable devices. It has several benefits, such as semi-permanent lifetime and weight reduction due to the needlessness of battery. Here, we investigate the mouse click motion of a finger for energy harvesting. Specifically, we focus on energy harvesting using the piezoelectric material, PVDF, attached to a robotic finger during mouse click motions. The piezoelectric material is attached to the robotic finger by wearing a glove with a pocket. By using the robotic finger, we remove the variation from the human motion, and quantitatively analyze the energy harvesting. We develop a modeling framework for the electromechanical behavior of the energy harvesting system to predict the energy harvested from the mouse click motion of the finger. Therein, the finger motion is considered as a three degree of freedom mechanism consisting of three links in a plane, and the electromechanical coupling of the piezoelectric material is described through a relationship between its stored charge and rotation angle. The resulting electromechanical model allows for predicting the harvested energy from the piezoelectric material for the mouse click motion as a function of the shunting load resistance. Model results are validated against experimental findings that demonstrate the feasibility of energy harvesting from the mouse click motion. Additionally, we find that the harvested energy is optimized at the load resistance matched to the impedance of the piezoelectric material, and the maximized energy is a few nanoJoules.

10164-54, Session 10A

Design and test of a power-generated magnetorheological damper

Xian-Xu Bai, Qi Zou, Li-Jun Qian, Hefei Univ. of Technology (China)

Magnetorheological (MR) dampers are a semi-active controllable actuators featuring MR fluids. They are widely investigated in civil constructions, vehicular applications, and medical fields. However, the cost of the semi-active controllable systems based on MR dampers are too high (as compare to passive systems) and the systems require extra installation spaces, because of the electronic systems, such as power supply and system controller.

Aiming at integrating the characteristics of controllable damping force and power-generated performance for the vibration control systems into one MR damper, this paper proposes a power-generated MR damper. The proposed power-generated MR damper consists of a controllable damping mechanism and a power-generation mechanism. The controllable damping mechanism is realized by an annular rotary gap filled with MR fluids working in pure shear mode, and a ball-screw mechanism is employed to transform rotary damping force of the power-generated MR damper to linear one. The power-generation mechanism, which is adopted to convert the external vibration energy into electric energy to power the controllable damping mechanism based on Faraday's law of electromagnetic induction, is realized by a permanent magnet rotor and several stator coil windings. The characteristics of the controllable damping force and power generation are theoretically analyzed and experimentally tested. The realized power-generated MR damper is possible to tailor installation space and harvest wasted mechanical energy. In addition, it will dramatically reduce the cost of applications because of compact structure with usage of very small amount of MR fluids (around 110 ml), as compared with conventional MR dampers.

10164-55, Session 10A

Optimization of voltage output of energy harvesters with continuous mechanical rotation extracted from human motion

Evan Rashid, Armita Hamidi, Yonas Tadesse, The Univ. of Texas at Dallas (United States)

With increasing popularity of portable devices for outdoor activities, portable energy harvesting devices are coming into spot light. The next generation energy harvester which is called hybrid energy harvester can employ more than one mechanism in a single device to optimize portion of the energy that can be harvested from any source of waste energy namely motion, vibration, heat and etc. In spite of few recent attempts for creating hybrid portable devices, the level of output energy still needs to be improved with the intention of employing them in commercial electronic systems or further applications. Moreover, implementing a practical hybrid energy harvester in different application for further investigation is still challenging. This proposal is projected to incorporate a novel approach to maximize and optimize the voltage output of hybrid energy harvesters to achieve a greater conversion efficiency normalized by the total mass of the hybrid device than the simple arithmetic sum of the individual harvesting mechanisms. The energy harvester model previously proposed by Larkin and Tadesse [1] is used as a baseline and a continuous unidirectional rotation is incorporated to maximize and optimize the output. The device harvest mechanical energy from oscillatory motion and convert it to electrical energy through electromagnetic and piezoelectric systems. The new designed mechanism upgrades the device in a way that can harvest energy from both rotational and linear motions by using magnets. Likewise, the piezoelectric section optimized to harvest at least 10% more energy. To the end, the device scaled down for tested with different sources of vibrations in the immediate environment, including machinery operation, bicycle, door motion while opening and closing and finally, human motions. Comparing the results from literature proved that current device has capability to be employed in commercial small electronic devices for enhancement of battery usage or as a backup power source.

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10164-56, Session 10A

Topology synthesis of planar ground structures for energy harvesting applications

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The objective of this paper is to used topology optimization to design resonators with 1:n resonances undergo planar vibrations. The resonators are intended for the use of kinetic energy scavenging in signals that exhibit two dominant frequency components, i.e., a fundamental component with large energy content and secondary component with smaller energy content. This phenomenon is often seen in rotary machines; their frequency spectrum exhibits peaks on multiple harmonics.

Several theoretical resonators are known to exhibit 1:2 or 1:3 internal resonances, notably the L-shape beam. However, designing manufacturable resonators is still a daunting task. We formulate the problem in its non-dimensional form. In this way, we can eliminate the constraint on the allowable frequencies' bandwidth. The frequency can be obtained a posteriori by means of linear scaling. Conversely to other researchers, which use the clamped beam as initial guess, we synthesize the final shape starting from a ground structure (or structural universe). We remove of the unnecessary beams from the initial guess by means of a graph-based filtering scheme. The algorithm determines the simplest structure that gives the frequency's ratio sought. Within the optimization, the structural design is accomplished by a linear FE analysis. Finally, we present the performance of the structure under various excitations.

10164-57, Session 10A

3D-printed lens for structure-borne wave focusing and energy harvesting

Serife Tol, F. Levent Degertekin, Alper Erturk, Georgia Institute of Technology (United States)

In this paper, we explore 3D-printed Gradient-Index Phononic Crystal Lens (GRIN-PCL) for structure-borne focusing both numerically and experimentally. The proposed lens consists of an array of nylon stubs with different heights which is realized by 3D printing the PA2200 nylon. The orientation and height of the stubs are determined according to the hyperbolic secant gradient distribution of refractive index which is guided by finite-element simulations of the lowest asymmetric mode Lamb wave band diagrams. Then the fabricated lens is bonded to an aluminum plate to focus the wave energy in the structure. Under plane wave excitation from a line source, the wave focusing performance is first simulated in COMSOL Multiphysics® and it is seen that the focal points are consistent with the analytical beam trajectory results. Experiments are conducted with a scanning laser vibrometer and experimentally measured wave field successfully validates the numerical simulation of wave focusing within the 3D-printed GRIN-PCL domain. With a piezoelectric energy harvester disk located at the focal region of the GRIN-PCL larger power output is obtained as compared to the baseline case of energy harvesting without the GRIN-PCL on the uniform plate counterpart for the same incident plane wave excitation.

10164-58, Session 10B

Development of haptic system for surgical robot

Han-Gyeol Gang, Jiong Min Park, Kumoh National Institute of Technology (Korea, Republic of); Seung-Bok Choi, Inha Univ. (Korea, Republic of); Jung Woo Sohn, Kumoh National Institute of Technology (Korea, Republic of)

For the advantages of small scar, low infection rate and rapid recovery, the demands and applications are rapidly increased for robot assisted minimal invasive surgery. Generally, the robot assisted surgery is processed by the communication between master console and slave robot instruments. However, only the visual information obtained by the slave camera is provided to operator via master console, the absence of tactile information can decrease the immersion and reality of operator and finally the performance of surgery also can be decreased. To generate and provide haptic information to operator, many research works has been carried out and positive applications are suggested. But, most of the previous haptic system has bulky mechanism and complex control method and then it is difficult to be applied to real field. In this paper, a new type of haptic system is proposed and its performances are evaluated. The proposed haptic system consists of effective master device and precision slave robot. The master device has 3-DOF rotational motion as same as human wrist and lightweight structure with gyro sensor for position measurement and small-sized MR brake for haptic actuator. The slave robot has 3-DOF rotational motion using servomotors and five bar linkage and torque sensor. It has been demonstrated that the proposed haptic system has good performances on tracking control of repulsive torque and desired position and it can be effectively applied to system in real field.

10164-59, Session 10B

Design and simulation of a new bidirectional actuator for haptic systems featuring MR fluid

Nguyen Quoc Hung, Vietnamese-German Univ. (Viet Nam); Diep Bao Tri, Ngoc Diep Nguyen, Ho Chi Minh Univ. of Industry (Viet Nam); Seung-Bok Choi, Inha Univ. (Korea, Republic of)

In this research, a new configuration of bidirectional actuator featuring MR fluid (BMRA) is proposed for haptic application. The proposed BMRA consists of a driving disc, a driving housing and a driven disc. The driving disc is placed inside the driving housing and rotates counter to each other by a servo DC motor and a bevel gear system. The driven shaft is also placed inside the housing and next to the driving disc. The gap between the two disc and the gap between the discs and the housing are filled with MR fluid. On the driven disc, two mutual magnetic coils are placed. By applying currents to the two coils mutually, the torque at the output shaft, which is fixed to the driven disc, can be controlled with positive, zero or negative value. This make the actuator be suitable for haptic application.

After a review of MR fluid and its application, configuration of the proposed BMRA is presented. The modeling of the actuator is then derived based on Bingham rheological model of MRF and magnetic finite element analysis (FEA). The optimal design of the actuator is then performed to minimize the mass of the BMRA. From the optimal design result, performance characteristics of the actuator is simulated and detailed design of a prototype actuator is conducted.

10164-60, Session 10B

Design and evaluation of a 2D haptic joystick featuring bidirectional magnetorheological actuator

Quoc Hung Nguyen, Vietnamese-German Univ. (Viet Nam); Bao Tri Diep, Ngoc Diep Nguyen, Dai Hiep Le, Industrial Univ. of Hochiminh City (Viet Nam)

In this work, a 2D Haptic Joystick Featuring Bidirectional Magnetorheological Actuator (BMRA) is proposed, optimally designed and experimentally verification. After an introduction of MR fluid and its application in haptic systems, the configuration of the proposed haptic joystick featuring two BMRAs is presented. Then, the optimal design of the BMRA is performed considering the maximum torque and mass of the actuator. From the optimal design result, performance characteristics of the actuators are simulated and detailed design of the prototype actuators is conducted. The 2D haptic joystick is then designed and a prototype is manufactured. Performance characteristics of the haptic joystick is then experimentally investigated and compared with simulated results.

10164-61, Session 10B

Design and control of a 7-DOF slave robot integrated with a magneto-rheological haptic master

Yong-Hoon Hwang, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

In this study, a 7-DOF slave robot integrated with the haptic master is designed and its dynamic motion is controlled. The haptic master is made using a controllable magneto-rheological (MR) clutch and brake and it provides the surgeon with a sense of touch by using both kinetic and kinesthetic information. Due to the size constraint of the slave robot, a wire actuating is adopted to make the desired motion of the end-effector instead of a conventional direct-driven motor. After conforming all motions of the slave robot such as yaw and roll by piloting the haptic master, a simple cutting surgery is undertaken. In the cutting surgery, various tissues which have different stiffness and damping are used and cutting accuracy is also evaluated by observing the cutting line divided into two sections; original color and indexed color. In addition, in order to demonstrate the effectiveness of the proposed system, a psycho-physical test is conducted by many different operators who can feel the different repulsive force or torque generated from the haptic master which is equivalent to the force or torque occurred in the cutting place.

10164-62, Session 11A

Metamaterial-based energy harvester design: prevention of wave cancellation

Yong Chang Shin, Soo-Ho Jo, Heonjun Yoon, Byeng D. Youn, Seoul National Univ. (Korea, Republic of); Miso Kim, Choon-Su Park, Wonjae Choi, Korea Research Institute of Standards and Science (Korea, Republic of)

Metamaterial-based energy harvesting (MBEH) has been recently introduced as means to enhance energy conversion efficiency by manipulating wave propagation. Metamaterials are assembled structures of multiple identical units, exhibiting exotic properties such as negative bulk modulus and negative mass in an effective manner. Bandgap, one of the unusual phenomena of the metamaterials, reflects all incoming waves, thereby being capable of focusing waves with the specially configured deployment of the subunits. This focused waves can be conveyed to an energy transduction media (e.g., piezoelectric material), yielding higher output power through the energy harvesting device. While focusing mechanisms using the metamaterials has been heavily studied, only limited research has addressed wave cancellation to enhance the focusing performance. In this study, we thus propose a new parabolic phononic crystal (PnC) design configured with quarter-wave stack (QWS) unitcells to avoid wave cancellation at the focal region. Under the plane wave assumption, the incident waves are reflected from the phononic bandgap structure and gathered at the focus of the parabola. Moreover, since the QWS configuration makes all the reflected waves in-phase, highly constructive interference can occur at the focal region when the phases of the incident and reflected waves are tailored to be the same. Finally, for the purpose of verifying the superior merits, the proposed design is compared to the PnC which has bandgap but is composed of the non-QWS unitcells.

10164-63, Session 11A

Adaptive piezoelectric metamaterial for wave attenuation and energy harvesting

Jiawen Xu, Shilong Li, Jiong Tang, Univ. of Connecticut (United States)

Piezoelectric metamaterials with LC shunt circuits are widely used in acoustic wave attenuation and guiding. Due to electro-mechanical coupling of piezoelectric element and local resonance from shunt circuits, this type of metamaterial has advantages of adaptiveness. In this research, we apply the piezoelectric metamaterials into acoustic energy harvesting. A unitcell of the piezoelectric metamaterials consists of host medium, two piezoelectric transducers attached onto the top and bottom of the host plate (bimorph) and external shunt circuits. The external shunt circuits create the local resonance for bandgaps and at the same time transfer the acoustic energy into electrical energy. The acoustic waves are thereby attenuated, transferred and stored in electrical level. Unlike the 2nd order system based energy harvesters, the operational frequency of such a metamaterial can be arbitrarily tuned by adjusting the external shunt circuits. Theoretical modeling, FEM simulation and experiments are presented to analyze the performance of the system.

10164-64, Session 11A

Experimental demonstration of metamaterial-based elastic energy focusing and harvesting

Miso Kim, Choon-Su Park, Wonjae Choi, Korea Research Institute of Standards and Science (Korea, Republic of); Yong Chang Shin, Soo-Ho Jo, Heonjun Yoon, Byeng D. Youn, Seoul National Univ. (Korea, Republic of)

Mechanical energy harvesting has drawn considerable attention as an attractive powering technology which enables sustainable self-powered operation of small electronics such as wireless sensors. A key challenge is still insufficient power generation for practical applications. In order to tackle the problem, we focus on amplification of input mechanical energy into the energy harvesting system through metamaterials instead of materials or device development for higher efficiency. Metamaterials, artificially engineered materials, exhibit unique properties including bandgap and negative refractive index and thus enable us to manipulate mechanical wave propagations. Wave guide and localization toward a desired position can lead to maximization of harvestable input mechanical energy. Recently, several research efforts on metamaterial-based enhancement of energy harvesting have been reported, but mostly based on intuitive design or with little experimental support. Our objective in this work is to investigate the effect of metamaterials on energy focusing and harvesting. With this purpose in mind, we experimentally evaluate harvesting performance as well as elastic wave propagation with two prototypes of metamaterials that are systematically designed through optimization process: 1) phononic crystals with a single defect and 2) parabolic elastic mirrors with phononic crystals. Correlation on theoretical analysis and experimental results is thoroughly studied and will be discussed. This talk will also address relevant experimental setup and optimal measurement conditions in detail.

10164-65, Session 11A

Wind energy harvesting with Halbach array

Kevin Wang, Ya S. Wang, Stony Brook Univ. (United States)

Vibration energy is one of the most common sources of energy that can be harvested from. Two vibration-to-energy conversion mechanisms are piezoelectric and electromagnetic [1,3]. The vibration of a cantilever beam is a popular method to harvest energy from piezoelectric and electromagnetics. When a cantilever beam vibrates from an external force the beam deflects back and forth. A piezoelectric material produces energy from the strain the beam is under. An electromagnetic array produces energy as a coil that is attached to the beam moves across the magnetic field of the array. More energy can be produced when a coil moves through a larger and more concentrated magnetic field. We propose a two degree of freedom aeroelastic energy harvester that uses a Halbach electromagnetic

array and microfiber composite (MFC) piezoelectric patches, shown in Fig. 1. A Halbach array is a specific arrangement of magnets that focuses the magnetic field onto one side of the array while negating the field on the other side [2] whereas a normal alternating array has its magnetic field even distributed both sides of the array. The microfiber composite (MFC) patch is primarily for increasing the stiffness while negligibly increasing the mass of the cantilever beam. Wind tunnel test results are presented to characterize power output and the flutter speed of the energy harvester at different wind speeds. The harvester reaches the flutter speed at 3.5 m/s and operates up to 5 m/s and produces a power of 300 mW. The harvester is compact and fits inside an 8in square duct.

10164-66, Session 11A

Luneburg lens for omnidirectional structure-borne wave focusing and energy harvesting

Serife Tol, F. Levent Degertekin, Alper Erturk, Georgia Institute of Technology (United States)

In this paper, a Luneburg lens is explored for omnidirectional structure-borne wave focusing both numerically and experimentally. The proposed lens is formed by radially distributed blind holes with different diameters. The radial orientation and diameter of the holes are determined according to the refractive index distribution which is guided by finite-element simulations of the lowest asymmetric mode Lamb wave band diagrams. According to this design, the wave travels slower at the center of the lens and converge at the focal spot which is on the circular lens boundary. Wave simulations are performed in COMSOL Multiphysics® under plane wave excitation from a line source and wave focusing is observed at the opposite border of the lens with respect to the incoming wave direction. Experimentally measured wave fields with a scanning laser vibrometer successfully validates the numerical simulation of wave focusing. Furthermore, omnidirectionality is verified by testing the lens under plane wave excitation from different directions. With piezoelectric energy harvesters located at the boundary of the Luneburg lens substantially larger power output can be obtained as compared to the baseline case of energy harvesting without the lens on the uniform plate counterpart for the same incident plane wave excitation.

10164-67, Session 11B

Metamaterial-inspired piezoelectric system with dual functionalities: energy harvesting and vibration suppression

Guobiao Hu, Lihua Tang, Raj Das, The Univ. of Auckland (New Zealand)

Vibration energy harvesting is a promising solution for low power electronics to get rid of batteries that need to be replaced or recharged constantly and has attracted wide research interests in recent years. Acoustic-elastic metamaterial is a kind of artificial material with engineered micro-structures and the applications can be found where environmental vibrations exist and need to be suppressed. Vibrations of the main structure made of acoustic-elastic metamaterials within the frequency range around the resonant frequency of the local resonator can be absorbed and attenuated. Combining these two concepts, this paper presents a metamaterial-inspired piezoelectric system that possesses simultaneous energy harvesting and vibration suppression functionalities. First, the concept of the proposed system is described and a corresponding lumped parameter model is established. The lumped parameter model demonstrates the effects of system parameters on the energy harvesting and the vibration suppression performances respectively. A remarkable finding is the double-valley phenomenon that intensively widen the band gap under strong electromechanical coupling condition. Subsequently, a finite element (FE) model is developed to predict the power and the transmittance responses of the system. The power output and the transmittance in the frequency domain are then predicted from the FE model. The FE results are qualitatively consistent with the analytical results with the lumped parameter model and reveal the double-valley phenomenon. Finally, a physical prototype is prepared and an experiment is conducted to confirm conclusions from the analytical and FE models.

10164-68, Session 11B

A continuous switching model for piezoelectric state switching methods

Garrett K. Lopp, Jeffrey L. Kauffman, Univ. of Central Florida (United States)

Piezoelectric-based, semi-active vibration reduction approaches have been studied for over a decade due to their potential in controlling vibration over a large frequency range. Previous studies have relied on a discrete model when switching between the stiffness states of the system. In such a modeling approach, the energy dissipation of the stored potential energy and the transient dynamics, in general, are not well understood. In this paper, a switching model is presented using a variable capacitance in the attached shunt circuit. When the switch duration is small in comparison to the period of vibration, the vibration reduction performance approaches that of the discrete model with an instant switch, whereas longer switch durations lead to less vibration reduction. An energy analysis is then performed that results in the appearance of an energy dissipation term in the shunt circuit.

10164-69, Session 11B

Automobile brake squeal noise suppression by piezoelectric-based dither control

Jaehan Park, Jeongha Song, Gyuhae Park, Chonnam National Univ. (Korea, Republic of); Taeho Jung, Jeongkyu Kim, Hyundai Motor Co. (Korea, Republic of)

Automobile brake squeal noise, which is friction induced vibration in frequency range of 1 kHz to 20 kHz, still remains a major problem for the automotive industry. This paper presents an analytical and experimental investigation into the application of “dither” control for the active noise control and suppression of automobile disc brake squeal. Dither is a concept of active noise control introducing high-frequency control effects into a system to suppress a lower-frequency disturbance. First, a numerical approach was conducted with the developed finite element model, and the effect of the dither control parameters of the brake system was examined. A specially designed brake system was then built and the dither control was applied for experimental verification with the identified parameters. The dither force was generated by a piezoelectric (PZT) stack actuator in the piston of a floating caliper brake. The performance of dither control was also compared with the results produced by an active control technique, such as positive position feedback (PPF). The results indicate that dither control could effectively suppress the brake squeal noise.

10164-70, Session 11B

Multi-objective optimization of piezoelectric circuitry network for mode delocalization and vibration suppression of bladed disk

Jiong Tang, David Yoo, Univ. of Connecticut (United States)

When the inter-blade coupling is weak, the bladed disk is highly susceptible to vibration localization, which can be caused even by very small mistuning in blades. When vibration localization occurs, not only vibration modes are localized, but also there are many detrimental effects on the dynamic response of a bladed disk, one of which is excessive amplification of the maximum forced response. Previous studies have indicated that these phenomena can be effectively alleviated through piezoelectric circuitry networking technique. Although some of these studies did parametric analyses on the circuit components, of which the main components are inductor, resistor, and coupling capacitor, systematic and mathematical optimization methods to determine their best values have not been yet developed. In this research, optimization methods to find the optimal values for piezoelectric circuit components are developed, concerning both vibration suppression of the maximum forced response and modes delocalization. To apply highly efficient sensitivity-based method, sensitivities of vibration suppression and delocalization with respect to circuit components are analyzed. While sensitivities of multiple harmonic vibration suppression with respect to circuit components can be analytically derived, vibration delocalization in terms of circuit components is not explicitly given. Hence, the functional relationship is firstly obtained by the regression technique, and then its sensitivity is analyzed. Since their optimal values are different depending on which objective, either vibration suppression or delocalization, is more weighted, multi-objective optimization is formulated based on the weighted sum method, which can be solved using the developed sensitivities. Case studies demonstrate that the proposed methods can efficiently find optimal values for piezoelectric circuit components.

10164-71, Session 11B

Enhanced synchronized switch damping control to cancel out the beating phenomenon

Gabriele Cazzulani, Marco Costantini, Francesco Braghin, Politecnico di Milano (Italy)

Synchronized Switch Damping control is one of the most interesting solutions for vibration suppression proposed in the last years. It is based on the electromechanical coupling provided by piezoelectric actuators. By connecting the piezoelectric actuator to a shunting circuit (typically a RL one) and properly switching between open and closed circuit, an equivalent hysteresis cycle is created and the structure energy is dissipated.

It is known that, in order to maximize the damping effect the resistance of the circuit must be reduced. Anyway, as shown in literature, this effect is limited by the presence of a beating effect when the resistance is lower than a certain threshold.

The aim of this paper is to analyse the beating phenomenon in order to propose new solutions to cancel it. The paper will show some innovative solutions modifying the shunting circuit to avoid the beating phenomenon and thus increase the control performance. These solutions will be described from a theoretical point of view and then tested to demonstrate their effect.

10164-72, Session 12A

MR fluid filled spring for vibration control

Stanislav Sikulskyi, Daewon Kim, Embry-Riddle Aeronautical Univ. (United States)

A mechanical spring filled with magnetorheological (MR) fluid is studied to achieve improved dynamic characteristics and to actively control structural vibrations. The hollow stainless steel spring filled with MRF-132DG is subjected to a controlled magnetic field in order to change the viscosity of the filled MR fluid and thereby to change the overall stiffness of the spring. Theoretical, numerical, and experimental analysis are performed in this study. MR fluid is modeled as a Herschel-Bulkley viscoplastic non-linear material in the mathematical model. In vibration damping applications, high shear rates of MR fluid lead to their large magnitudes of the shear stress components. Shear rates is therefore an important parameter that needs to be investigated for the filled MR fluid for different magnetic fields. The MR fluid filled spring is also numerically modeled using commercial software to characterize dynamic structural responses of the spring as well as to obtain MR fluid motion during spring vibrations. Finally, multiple experiments are conducted to validate the mathematical and the numerical models. Here, the spring is subjected to low and high frequency tensile loadings using a universal testing machine. The results show that a significant amount of stiffness can be added to the spring by controlling the MR fluid viscosity. The results show that this MR filled spring damping system can be a lightweight intelligent tool for vibration control applications, especially for high frequency and high amplitude products.

10164-73, Session 12A

The role of vibration absorbers in chiral lattice metastructures

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Passive metamaterial-inspired vibration suppression systems, or metastructures, have recently emerged as a way to enhance structures to include vibration attenuation. One popular design of metastructure includes a repeating chiral lattice comprised of an absorbent viscoelastic material with a stiff load bearing outer frame. This design often has annular inclusions throughout the lattice that house tuned masses acting as local resonators. Both the lattice and annular masses are used to attenuate vibration at chosen frequency ranges. These designs have been proven to be effective in reducing low frequency global structure vibration levels as well as tuned vibration reduction. Work to optimize these structures has focused on the design of the individual components in the structure as well as the distribution of annular inclusions within the beam. While these optimizations consider the changing geometry of the structure, they lack consideration for the viscoelastic materials. Due to the high amount of inherent material damping in viscoelastic materials, these lattice structures may experience improvement from by the material properties rather than the absorber design. Experimental modal analysis results will compare the vibration reduction in chiral lattice metastructures due to viscoelastic materials and those due to absorbers while modeling of the structure will help extend the tradeoff consideration between material damping and vibration absorption to future designs.

10164-74, Session 12A

Measured performance of a semi-active tuned mass damper with acceleration feedback

Marcin Maslanka, AGH Univ. of Science and Technology (Poland)

Semi-active tuned mass dampers (STMDs) with magnetorheological (MR) dampers are becoming promising alternative to passive tuned mass dampers (TMDs) and active tuned mass dampers (ATMDs). In this paper, a new control algorithm for STMDs with acceleration feedback is investigated and experimentally evaluated in a laboratory wind tower - nacelle model equipped with STMD. The STMD consists of its mass, passive springs and a real-time controlled small-scale MR damper. The new control algorithm for STMDs is developed by modifications of an existing acceleration feedback control approach which was originally proposed for ATMDs. The simulation results demonstrate that the STMD with modified acceleration feedback performs equally well as the TMD with five times larger mass. This paper compares the measured and the simulated steady-state frequency responses of the novel STMD and discusses the major deteriorating factors that limit the measured performance of the STMD.

10164-75, Session 12A

A fail-safe liquid spring-controllable magnetorheological damper system for three-dimensional earthquake isolation system

Sevki Cesmeci, Faramarz Gordaninejad, Keri Ryan, Walaa Eltahawy, Univ. of Nevada, Reno (United States)

Earthquake-induced damage to the building load carrying components, nonstructural components (architectural and mechanical systems), and internal equipment or contents, is still expected in code compliant buildings. Recent earthquakes have shown that economic losses are dominated by damage to nonstructural components and contents. Seismic isolation systems, which consist of a flexible layer of rubber or friction bearings separating the building from its foundation, are effective in protecting buildings from damage due to horizontal (in-plane) ground shaking. However, recent realistic large-scale earthquake shaking tests have shown that nonstructural components and contents in isolated buildings are susceptible to damage from vertical (out-of-plane) motion. In this study, a fail-safe liquid spring controllable magnetorheological (MR) damper system is designed, built and tested. The device combines the fail-safe viscous damping with the controllable MR damping and liquid spring features on a singles unit serving as the vertical component of the building suspension system itself. In a scaled 3D earthquake, the device is not only subjected to vertical forces but also large horizontal forces up to 28,000 kN. The experimental set-up and procedure is discussed and the results are presented.

10164-76, Session 12A

An adaptive magnetorheological elastomer bridge bearing

Siddaiah Yarra, Majid Behrooz, David Mar, Nathan Pinuelas, Blake Muzinich, Gokhan Pekcan, Ahmad M. Itani, Nelson G. Publicover, Faramarz Gordaninejad, Univ. of Nevada, Reno (United States)

This study presents the design, development, testing and evaluation of a scaled adaptive bridge bearing with lateral stiffness controllability capabilities. The bearing features Magnetorheological Elastomer (MRE) layers as adaptive elements which allow for an increased stiffness under a magnetic field. The adaptive bridge bearing incorporates a closed-loop magnetic circuit that results in an enhanced magnetic field in the MRE layers. A test setup for applying simultaneous variable shear, constant compression, and variable magnetic field on the bearing is designed and fabricated. Results of the sensing experiments shows the capability of MRE layers for sensing structural loads. The tunable bridge bearing results demonstrate the ability of the bearing in changing its stiffness under different magnetic field, compressive, and shear loads.

10164-77, Session 12B

Bistability and variable stiffness of cellular solids designed based on origami patterns

Sattam Sengupta, Suyi Li, Clemson Univ. (United States)

The application of origami-inspired design in engineering structures has been the subject of much research efforts. These structures, inspired from different types of origami patterns are capable of displaying a host of innovative mechanical characteristics which conventional structures do not possess. Using one type of origami, namely, the Miura Ori folding pattern and applying certain specific design constraints to this patter, it is possible to design a unit Miura cell. By suitably modifying the crease pattern of this unit cell, it can display an unconventional bistable behavior over a specified range of design. This bistability can be controlled by changing the folding angle of the Miura origami pattern. Within the design space where the unit cell possesses bistability, the stiffness of the cell also differs across its stable configurations. This variable stiffness can be tuned by tailoring the crease pattern of the cell. Due to the unusual bistable behavior of the cell, two distinct force-deflection curves exist which lead to the existence of two elastic moduli, the difference of which can also be varied by modifying the cell crease parameters. The unique mechanical properties stemming from the design of such a unit cell can be advanced further by assembling these cells into a structure which can be capable of shape morphing along with programmable stiffness and elastic modulus.

10164-78, Session 12B

Optimization design of an adaptive CFRC reflector for high order wave-front error control

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The trend in future space high precision reflectors is going towards large aperture, lightweight and actively controlled deformable antennas. An adaptive shape control system for a Carbon Fiber Reinforced Composite (CFRC) reflector is conducted by Piezoelectric Ceramic Transducer (PZT) actuators. This adaptive shape control system has been shown to effectively mitigate common low order wave-front error, but it is inevitably plagued by high order wave-front error control. In order to improve the controllability of the adaptive CFRC reflector control system for high order wave-front error, the design of adaptive CFRC reflector requires optimizing further. According to numerical and experimental results, the print-through error induced by manufacturing and PZT actuators actuation is a type of predominant high order wave-front errors. This paper describes a design which some secondary rib elements are embedded within the triangular cells of the primary ribs. These small secondary ribs are designed to support the reflector surface's weak region. Controllability of this new adaptive CFRC reflector control system with small secondary ribs is evaluated by generalized Zernike functions. This new design scheme can reduce high order residual error and suppress the high order wave-front error such as print-through error. Finally, design parameters of the adaptive CFRC reflector control system with small secondary ribs, such as primary rib height, secondary rib height, cut-out height of primary rib, are optimized.

10164-79, Session 12B

Design of a 3D printed lightweight orthotic device based on TCP muscle: iGrab hand orthosis

Lokesh Kumar Saharan, Monica Jung de Andrade, The Univ. of Texas at Dallas (United States); Tiffany Jefferson, Lynntech (United States); Ray H. Baughman, Yonas Tadesse, The Univ. of Texas at Dallas (United States)

Partial or total upper extremity impairment affects people's quality of life due to stroke, neuromuscular disease, or trauma. Many researchers have presented orthotic hand designs to addresses the need of rehabilitation or assistance on upper extremity functionality. Most of the devices available commercially and in literature are non-customizable and powered by conventional actuators such as DC motors. This study presents a hand orthosis termed iGrab, a novel, customizable, 3D printed, lightweight exoskeleton based on recently reported Twisted and Coiled Polymer (TCP) muscles, which are lightweight, high power to weight ratio and large stroke. We used silver coated nylon 6,6 threads to make TCP muscles that are electro-thermally actuated. Here, we present the preliminary results of one finger actuation with two different designs.

10164-80, Session 12B

Active control of tail fin for power regulation on a wind turbine of low power

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This work presents a new approach of control on the tail fin of wind turbines of low power. The power regulation performs in a wind turbine of 1 Kw considering several records winds like the Istmo de Tehuantepec in Oaxaca, México. The mathematical model is obtained from the formalism of Lagrange given the ratio of wind capture between the wind rotor and the area of contact with the surface of tail fin. The active control aims to optimize the efficiency of the wind turbine, reducing the gyroscopic movement of the overall structure, due to sudden changes of orientation by stochastics components of speed and directions of wind. A sliding mode control is designed through a DC motor coupled to the tail fin. Finally, we show some numerical results in order to observe the performance of the power regulations of the overall system.

10164-81, Session 13A

Geometry optimization of permanent magnet magnetorheological damper constrained in a specific volume

Tae-Hoon Lee, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

In this work, a novel type of the permanent magnet magneto-rheological (PMMR) damper is introduced and optimally designed to maximize the field-dependent damping force with a volume constrant. Unlike a typical MR damper activated by the magnetic coils, PMMR does not require the magnetic circuit. Instead of using the magnetic circuit, the permanent magnet is attached to the pistion and hence the field-dependent damping force can be achieved by the piston movement. This is possive because the PMMR is designed such that the magnetization area of the piston housing is changed due the shape design of the piston. As a result, this leads the change of magnetic flux density and hence the damping force is controlled by the location of the magnet. In this work, the geometry optimization of PMMR damper is undertaken to maximize the damping force range by the magnetization area variation in the same geometry constraint. In order to achieve this objective, an analytical model is formulated and design parameters of PMMR damper such as the size of permanent magnet and orifice gap are investigated by numerical analysis. Sequentially, the effectiveness of this optimization is validated by comparing the magnitude of the damping force between the initial design and optimal design.

10164-82, Session 13A

Weight and space saving design of energy-efficient MRF-based clutches for hybrid powertrains

Christian Hegger, Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

The requirements for transmission and coupling elements in hybrid powertrains are rising continuously. Our previous investigations were focused on the elimination of viscous induced drag torques in switch elements based on magnetorheological fluids by a MR-fluid movement control. MRF's are highly qualified for the utilization in powertrains considering their particular characteristics of changing their apparent viscosity significantly under influence of a magnetic field by fast switching times and a smooth torque control. In this contribution a further developed design of the magnetic circuit will be presented to reduce the weight and space requirements of energy-efficient MRF-based actuators. These requirements are satisfied by a serpentine flux guidance resulting also in a reduction of the excitation energy. The advantages will be illustrated by magnetically equivalent circuits. Also of interest are novel, space-saving combinations of a MRF-based brake and clutch due to the new design of the magnetic circuit. Subsequent, beside a simulation based design a MRF-based clutch is realized. The experimental investigation demonstrates fast torque transmission respond times and the elimination of viscous induced drag torques. Finally, the integration of a MRF-based brake and clutch in a novel two stage multi-mode-transmission will be presented.

10164-83, Session 13A

Optimal design and experimental analysis of a magnetorheological valve system for the vehicle lifter used in maintenance

Sang-Un Shin, Tae-Hoon Lee, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

This work presents a new type of vehicle lifter for precision position control using a magnetorheological valve system. In the first step, the principal design parameters such as gap size of oil passage, length and depth of coil part, and distance coil part from the end of valve are considered to achieve the objective function for getting the highest position accuracy under current input constraint. This optimization is undertaken by adopting a software in ANSYS. After determining the optimized design values, the field-dependent pressure drops of the optimized valve system are experimentally evaluated and compared to those obtained from the initial design. Subsequently, the position of the vehicle lifter is controlled by change of pressure drop using a couple of controllers;PID controller and sliding mode controller. It is demonstrated that the proposed vehicle lifter can be effectively applied to vehicle service center for more accurate tasks.

10164-84, Session 13A

Array type of MR sponge tactile sensor for medical applications

Seung-Woo Cha, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

Recently, great advanced technologies are being made in robot minimally invasive surgery (RMIS) and the commercialization is reached owing to high stabilization phase. However, there are some problems in the robot surgery. It is very hard to get the touch feeling of the organs during surgical operation in RMIS because the surgeons cannot touch and feel repulsive force from the organs directly. In order to resolve this problem, MR fluid which can generate the field-dependent yield stress is utilized to realize proper repulsive force of the organs. In the previous study, a single MR sponge was proposed to mimic human's organs. It consists of MR fluid, open celled polyurethane foam (sponge) and is covered with collagen film. Using the MR sponge cell, the viscoelastic sensational behaviors of human organs through controlling the current intensity can be easily realized. In this work, the array type of MR sponge that can realize simultaneously various tissues (organs) is proposed and its effectiveness is verified through experimental tests. The similarity between MR sponge and real organs is identified and desired repulsive force of each organ can be achieved by proper selection of MR spone cell as well as by controlling the input current (magnetic field).

10164-85, Session 13A

Design of a 7-DOF haptic master using a magneto-rheological devices for robot surgery

Seok-Rae Kang, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

This paper presents a 7 degrees-of-freedom (7-DOF) haptic master which is applicable to the robot-assisted minimally invasive surgery (RMIS). By utilizing a controllable magneto-rheological (MR) fluid, the haptic master can provide force information to the surgeon during surgery. The proposed haptic master consists of three degrees motions of X, Y, Z and four degrees motions of the pitch, yaw, roll and grasping. All of them have force feedback capability based on the mathematical models, and the proposed haptic master can generate the repulsive forces or torques by activating MR clutch and MR brake. Both MR clutch and MR brake are optimally designed and manufactured with consideration of the size and output torque which is usable to the robotic surgery. A proportional-integral-derivative (PID) controller is then designed and implemented to achieve torque/force tracking trajectories. It is verified that the proposed haptic master can track well the desired torque and force occurred in the surgical place by controlling the input current of MR clutch and brake.

10164-86, Session 13A

Sound transmission analysis of partially treated MR fluid based sandwich panels using finite element method

Masoud Hemmatian, Ramin Sedaghati, Concordia Univ. (Canada)

This study aims to develop a finite element model to predict the sound transmission loss (STL) of a multilayer panel partially treated with a Magnetorheological (MR) fluid (MRF) core layer. Prediction of the sound transmission across the partially treated sandwich panels enables engineers to design the panels with specific acoustical behaviors. Magnetorheological (MR) fluids are smart materials with the promising controllable rheological characteristics in which the application of an external magnetic field instantly changes their rheological properties. Partial treatment of sandwich panels with MR fluid core layer provides an opportunity to change stiffness and damping of the structure without significantly increasing its mass unit per area. Consequently, the acoustical behavior of the structure could be improved.

The STL of a finite sandwich panel partially treated with MR fluid is modeled using the finite element (FE) method. Circular sandwich panels with clamped boundary condition and elastic face sheets in which the core layer is segmented radially and circumferentially are considered as shown in Fig. 1. Figure 2 shows the two circular and annular finite elements with 6 and 12 degrees of freedom are utilized, respectively, for the development of the FE model. The transverse and shear deformation and also the rotary inertia of the elastic face sheets are neglected and the classical plate theory based on Kirchhoff's assumption is considered to obtain the displacements of the face sheets. The displacements of the core layer are then expressed as a function of the face sheets displacements utilizing the compatibility conditions. Using the stress-strain relationships given by hook's law, the strain and kinetic energies are obtained as a function of the shape functions of the plate finite element. The MR fluid core layer is considered as a viscoelastic material with complex shear modulus with the magnetic field and frequency dependent storage and loss moduli as reported in [1]. Neglecting the effect of the panel's vibration on the pressure forcing function, the work done by the acoustic pressure is expressed as a function of the blocked pressure in order to calculate the force vector in the equation of the motion of the panel [2]. The FE equation of motion of the MR sandwich panel is then developed to predict the transverse vibration of the panel which can then be utilized to obtain the radiated sound using Green's function [3]. The developed model is used to conduct a systematic parametric study on the effect of different locations of MR fluid treatment on the natural frequencies and the STL.

In order to experimentally investigate the STL of sandwich panels partially treated with MR fluid core layer, an experimental setup has also been designed as shown in Fig. 3. The setup includes a box with two anechoic spaces, the power supplies and the analyzer. The electromagnet has been fabricated with 4200 turns copper wire coil to provide sufficient magnetic field and has been placed between the anechoic spaces. Two type of sandwich panels with radially and circumferentially segmented core layer have been fabricated. Silicone rubber has been utilized in order to seal the sandwich panel and also for the segmentation.

The fabricated sandwich panel is partially treated with MR fluid (MRF 132DG manufactured by Lord Corporation [4]) and clamped at the center of the electromagnet to be subjected to magnetic field. A wide frequency range speaker (Behringer C50A Active 30 Watt) with homogeneous dispersion pattern has been place in the source room to provide the sound wave that hits the sandwich panel directly. In order to measure the STL of the panel, two high precision microphones were utilized in the source and the receiving rooms and the CPB analyzer has been employed to provide the STL. Moreover, a miniature three-axis accelerometer has been attached at the center of the panel to measure its acceleration which has then been further analyzed to evaluate the natural frequencies of the panel.

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10164-87, Session 13A

Design and evaluation of a shear-mode MR damper for suspension system of front-loaded washing machines

Quoc Hung Nguyen, Vietnamese-German Univ. (Viet Nam); Quoc Duy Bui, Long Vuong Hoang, Industrial Univ. of Hochiminh City (Viet Nam); Dai Hiep Le, Vietnamese-German Univ. (Viet Nam)

In this research, low damping force shear-mode magneto-rheological (MR) dampers that can replace conventional passive dampers of a front-loaded washing machine is designed and experimentally evaluated. In the design of the MR damper, required damping force, off-state friction force, size and low cost of the MR dampers is taken into account. Firstly, a suppression system for the washing machine featuring MR dampers is proposed considering required damping force, available space and cost of the system. Optimization of the proposed MR suspension system is then performed considering required damping force, off-state friction force, size, power consumption and low cost of the MR dampers. From the optimal results, simulated performance of the optimized MR damper is obtained and presented with discussions. A detailed design of the MR dampers is then conducted and a prototype MR damper is manufactured. In addition, experimental results on the prototype MR damper are obtained and compared with simulated ones. Finally, discussions on performance and application of the MR suspension system for front-loaded washing machines are given.

10164-88, Session 13B

Ultrasound acoustic energy transfer for cavitation bubble manipulation: nonlinear hydroelastic model

Marjan Bakhtiari Nejad, Ehsan Esmaili, Ahmed Elnahhas, Sunghwan Jung, Shima Shahab, Virginia Polytechnic Institute and State Univ. (United States)

Many bio-medical applications entail the problems of spatially manipulating of bubbles by means of ultrasound radiation force and their subsequent interaction with elastic materials; bubbles perform a very efficient conversion of acoustical energy to mechanical motion which induces local vibrations at a target material. The examples are ultrasonic noninvasive targeted drug delivery and therapeutic applications. In this present study, an analytical framework is introduced based on classical Rayleigh-Plesset equation to (1) investigate nonlinear ultrasound wave propagation in bubbly fluids and (2) characterize bubble-cloud dynamics near an elastic substrate. The coupled system dynamics under various conditions is studied. Specifically relationship between the vibration amplitude of bubbles with system parameters, such as the intensity and spatial distribution of acoustic pressure wave, initial bubbles size, the distance of bubble-cloud to the substrate, and geometric and material properties of the substrate are studied. The induced stress field on the layer in response to the excitation frequency in the neighborhood of the bubble-cloud resonance frequency is also reported. Experiments are done for parameter identification and model validations.

10164-89, Session 13B

Probabilistic performance-based design for high performance control systems

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High performance control systems (HPCS) are advanced damping systems capable of high damping performance over wide performance bandwidth, ideal for mitigation of multi-hazards. They include hybrid, semi-active, and active damping systems. However, HPCS are more expensive than typical passive mitigation systems, rely on power and hardware (e.g., sensors, actuators) to operate, and require maintenance. In this paper, a life cycle cost analysis (LCA) approach is proposed to estimate the cost to benefit ratio of these systems over the entire life of the structure. The novelty resides in the formulation of a probabilistic approach in the control loop, whereas a probability of failure of the control system, estimated through inclusion of uncertainties in different components of the HPCS, is included. This yields a probabilistic performance-based design approach for HPCS. The approach includes power, sensor, and actuator failure, and accounts for possible mistuning of the controller. Numerical simulations are conducted on a building located in Boston, MA. LCA are conducted for passive control systems and HPCS. The concept of controller robustness is also demonstrated through LCA of an HPCS based on a decentralized and data-based adaptive controller. Results highlight the importance of the proposed probabilistic performance-based design procedure.

10164-90, Session 13B

Vibration control using a variable coil-based friction damper

Mohsen Amjadian, Anil Kumar Agrawal, The City College of New York (United States)

This paper is focused on the analytical model, design, and simulation of a variable coil-based friction damper for vibration control of structures. The proposed variable friction damper is composed of a soft-ferromagnetic plate, made of a linear magnetic material, and two identical rectangular air-core coils in parallel, each one attached to the plate through a friction pad. The friction force is provided by a normal force produced through a magnetic attraction interaction between the coils and the soft ferromagnetic plate when sliding relative to each other. The magnitude of the normal force in the damper is varied by a semi-active controller that controls the command current passing through the coils. To demonstrate the efficiency of the proposed variable friction damper and its semi-active controller, it has been implemented on a two-degree-of-freedom (2DOF) base-isolated model subjected to the acceleration components of three records of strong earthquakes. The results show that the performance of the proposed variable friction damper in its passive-on mode is overshadowed by the undesirable effects of the stick-slip phenomenon. However, the damper in its semi-active mode, because of acting completely in its sliding phase, is more successful not only in reducing the displacement of the base-floor but also in averting the stick-slip phenomenon.

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10165-1, Session 1

The effects of bonding layer on the high-frequency dynamic response of piezoelectric augmented structures

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Embedded and surface bonded piezoelectric wafers have been widely used for control, energy harvesting, and structural health monitoring applications. The basis for all these applications is the energy transfer between the piezoelectric wafer and the host structure, which takes place through the adhesive bonding layer. The characteristics of the bonding layer is found to have an important impact on the sensing and actuation capabilities of piezoelectric-based applications.

In this paper, the high frequency dynamic response of an elastic beam coupled with a piezoelectric wafer is investigated, including the bonding layer in between. A previously developed three-layer spectral element model, with high frequency capabilities, is utilized for this purpose. Timoshenko beam and elementary rod theories are adopted by the model to describe axial and lateral deformations in each of the three layers. A parametric study is conducted to evaluate the effects of bonding layer thickness and the modulus of rigidity on the steady-state response of the coupled system, including frequency response functions and electromechanical impedance. Numerical examples are presented to demonstrate the impact of bonding layer characteristics on piezoelectric-based structural health monitoring and energy harvesting applications.

10165-2, Session 1

Strain-powered ferroic antennas

John P Domann, Greg P Carman, University of California, Los Angeles (United States)

Electric antennas are still large structures (approximately 1m for 300 MHz operation), and have so far eluded the miniaturization trend common in the electronics industry. This is due in large part to an impedance mismatch with free space, and an increase in system losses from ohmic heating as antenna dimensions shrink. Recent work has proposed using multiferroic heterostructures to create small energy efficient antennas. This idea was first explored by Rowen's 1961 paper on electromagnetic (EM) radiation from YIG, and Mindlin's 1973 paper on radiation from quartz. Since then limited work has looked at EM radiation from adaptive materials, and there are currently no analytical models describing such a device. This presentation provides an analytical model to examine small mechanically powered energy efficient antennas.

An analytical framework is provided that couples elastodynamics and electrodynamics using piezoelectric and piezomagnetic constitutive behavior. This approach uses an eigenmode expansion of the undamped longitudinal vibrations in a prismatic rod to describe EM radiation from each harmonic mode. The problem is reduced to examination of damped harmonic oscillators, and EM radiation is shown equivalent to an effective volumetric strain-rate dependent damping. This approach provides the frequency response of a mechanical antenna, and demonstrates important scaling behavior relative to conventional antennas. Resonant analysis leads to simple closed form expressions for antenna efficiency, and leads to a metric directly comparing mechanical and conventional antennas, facilitating both material selection and device design. To summarize, this presentation provides a first look at the strain-mediated control of wireless communications.

10165-3, Session 1

Experimental study on relaxation properties of ionic polymer-metal composites

Bin Luo, Xi'an Jiaotong Univ. (China)

Relaxation properties of ionic polymer metal composites is related to Internal composition.In this paper, we first establish the index of quantitative relaxation deformation?then effects of the electrode? substrate and solvent on the relaxation properties are discussed to explain the nature of relaxation .Finally, the measures and methods are proposed to solve the relaxation.

10165-4, Session 1

Micro-mechanical analysis of piezo fibers composites through functional orthogonlization

Akshay Kumar, Srikant S. Padhee, Indian Institute of Technology Ropar (India)

Sensing and actuation of active control systems can be achieved in many ways, namely, mechanical, hydraulic, pneumatic and thermal. But piezoelectric materials draw much more attention when light weight constraints are imposed. In the beginning, piezo-ceramics and actuator patches were bonded to the surface of observation; however, continuous development has lead to inbuilt piezoelectric sensors and actuators. But brittleness of piezoelectric sensors and actuators shortens their life span, for which a new and advanced class of piezoelectric fiber reinforced composites (PFRC) has been developed. PFRCs contain unidirectional aligned piezoelectric fibers serving for stiffness to these composites, surrounded by matrix that provides damage tolerance mechanism. Furthermore, due to micro manufacturing of fibers lower number of defects is found in PFRCs. Low cost, better performance and ease to mold into desired shape are some other advantages of PFRCs. Moreover, an electrical signal can be passed through the fibers in PFRCs expanding the area of application to structural health monitoring, vibration sensing, controlled vibration damping, power generation from vibrations, additional load bearing capacity of composites and shape control through anisotropic actuation.

The linear behavior of piezo-ceramics is explained by linear piezoelectric constitutive models [1, 2], though they are incapable of explaining the non-linearity. However, an appropriate choice of strain/displacement relationships can partially introduce geometric non-linearity. A model to predict the nonlinear behavior of piezo-ceramics is discussed in [3] assuming material constants independent of the magnitude of stress/strain and electric field applied. Non-linear models are categorized into two groups [4] based on the implementation of high electric field [5] and due to polarization reversal in piezo-ceramics [6, 7]. But all these nonlinear models focus only on piezo-ceramics and piezoelectric crystals. Furthermore, assumptions as rectangular cross section of PFRCs in [4] do not lead to a generalized model.

An answer to this problem is the use of Variational Asymptotic Method (VAM) which is a powerful mathematical technique to solve problems seeking stationary point of a functional. In VAM, asymptotic expansion of functional space and application of variational method to each subspace ensures asymptotic correction of the solution reducing computational cost by about three orders of magnitude in comparison to rigorous 3D Finite Element Analysis (FEA) tools commonly available [cite: Nonlinear Composite Beam Theory D. H. Hodges]. VAM resolves a geometrically nonlinear three dimensional (3D) problem into linear two dimensional (2D) cross sectional analysis and nonlinear one dimensional (1D) analysis along the longitudinal axis. In the present study, VAM is employed for building a micromechanics model forecasting the nonlinear behavior of piezo-fibers, predicting the electro-mechanical coupling in piezoelectric fibers due to interaction between applied electric impulse and deformations. Asymptotic expansion of energy functional space into subspaces of energy based on extension, bending and twisting is carried out by means of VAM that will lead to generalized solution which is then extended to a specific problem. The results so obtained are validated with finite element analysis.

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10165-5, Session 1

Mechanoelectrochemistry of soft electroactive materials and biological tissues via surface-tracked scanning electrochemical microscopy

Vishnu Baba Sundaresan, Robert Northcutt, Vijay Venkatesh, John Parker Evans, The Ohio State Univ. (United States)

Mechanoelectrochemistry is the study of elastic and plastic deformation of materials during reversible reduction and oxidation processes. Time-correlated ion transport and associated volumetric changes in soft polymers and cells is essential to study the robustness of compliant battery electrodes and mechanobiology of cells in developmental biology respectively. These characterization methods required to investigate the chemical physics requires a spatial resolution of 10s of nanometers and a few MHz of bandwidth for video-rate imaging of an active site or a single cell. Towards this goal, Sundaresan and coworkers have developed an imaging technique on scanning electrochemical microscopy (SECM) hardware with shear force (SF) feedback, and have developed the necessary algorithms for high bandwidth dynamic mechanoelectrochemistry characterization (1, 2). Recently Sundaresan and coworkers have also demonstrated the use of polypyrrole-tipped SECM ultramicroelectrodes (UME) for near-field imaging of electrochemically active surfaces without a redox-mediator (3).

In these studies, it was demonstrated that the structural excitation to the glass electrode to perform SECM+SF imaging as surface-tracked scanning electrochemical microscopy (ST-SECM) requires to be reduced significantly for imaging soft materials, especially cells. In this proceedings article, we demonstrate necessary modifications to the ST-SECM electrode to reduce the energy imparted for imaging by structural modifications via a coupled dynamic structural model. Using geometries derived from this structural model, we demonstrate a novel fabrication method using hydrofluoric acid etch to produce electrodes of controlled dimensions. The electrodes are made from quartz glass, have an RG of 5-10, electroactive dimeter of 100-500nm and 20mm long are used for imaging neuronal cells from the glia of a mouse and three-dimensional maps of surface topography and ion transport activity. Custom PIC piezoelectric wafers measuring 3mm x 3mm are used as dither and receiver for SF-imaging. In addition, we also show methods to derive mechanical properties (rigidity modulus) of the cell layer from ST-SECM measurements.

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10165-6, Session 2

Numerical investigation of crack propagation direction in ferroelectric actuators

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The functionality of smart structures and microelectromechanical systems, such as ferroelectric multilayer actuators (MLA), macro-fiber composites, etc., can be essentially influenced by crack formation.

In the current research possible cracking patterns in PZT MLAs are numerically modeled by finite element method (FEM). Fully coupled electro-mechanical FE analysis is used to investigate the MLA behavior during poling process and under subsequent in-service electromechanical loading.

Ferroelectric user elements are developed for commercial software ABAQUS to mimic micromechanical non-linear bulk material behavior. They allow to simulate realistically the poling process of ferroelectric ceramics as a result of tetragonal domain switching.

It is known from the experimental results, that cracks mainly originate from an electrode tip and then propagate along the electrode interface. There are as well oblique cracks and cross-cracks observed in MLAs. In many cases the type and direction of emerging cracks depend on cofired, non-cofired or semi-cofired boundary conditions.

Initially, the direction of maximum tangential stresses are studied at different positions along the electrode plane. Then electro-mechanical cohesive elements (EMCZE) are inserted between the bulk ferroelectric elements perpendicular to the direction of action of the maximum tangential stresses. Damage in the CZE is accumulated in accordance with the traction-separation law.

As a result of the simulations different patterns of crack propagation in MLAs with cofired, non-cofired or semi-cofired electrode geometry are found and studied. The numerical results coincide with the experimental observations and lead to a better understanding of the complicated multi-physics processes taking place in smart structures.

10165-7, Session 2

A quantum-informed homogenized energy model for ferroelectric materials

Lider Leon, Ralph C. Smith, North Carolina State Univ. (United States); Wiiliam S. Oates, Paul Miles, Florida State Univ. (United States)

In this presentation, we will discuss the development and implementation of a multiscale model to quantify rate-dependent hysteresis in ferroelectric materials. In the first step of the development, we will employ density function theory (DFT) to map out an energy surface for the polarization and strains for a single domain structure. We will subsequently employ this energy to construct a macroscopic homogenized energy model (HEM) that quantifies the hysteresis and constitutive nonlinearities inherent to ferroelectric compounds. To incorporate the effects of multiple domains and grains in polycrystalline compounds, we treat the coercive and interaction fields as distributed with probability density functions that we construct using macroscopic data. Attributes of the model will be illustrated with experimental data.

10165-8, Session 2

Bayesian uncertainty analysis of continuum phase field modeling in ferroelectric materials

Paul Miles, William S. Oates, Florida State Univ. (United States); Lider Leon, Ralph C. Smith, North Carolina State Univ. (United States)

The evolution and formation of domain structures in ferroelectric materials is modeled using a continuum phase field approach and compared with density functional theory (DFT) using Bayesian uncertainty analysis. These simulations are carried out on the ferroelectric, lead titanate. Self-consistency between DFT and the continuum approach has remained a challenge. There is uncertainty in the phenomenological parameters related to the Landau energy, electrostriction, and twinned domain wall energy in single and polydomain ferroelectric crystals. To quantify the model parameter uncertainty associated with the phase field model, Bayesian statistics were used. Specifically, we consider the uncertainty related to approximating the lattice strain and full-field electron density as a homogenized, electromechanical continuum. The uncertainty is propagated through the model, allowing us to obtain prediction and credible intervals when estimating the non-convex energy surface, electrostrictive stresses, and domain structure characteristics for lead titanate. Our results highlight the areas of larger uncertainty and provide insight into model enhancement. Furthermore, the phase field model predictions for 180 degree and 90 degree domain wall sizes and energies agree well with DFT calculations.

10165-9, Session 2

Model development for PZT bimorph actuators employed for micro-air vehicles

Nikolas Bravo, Ralph C. Smith, North Carolina State Univ. (United States); John Crews, Applied Research Associates, Inc. (United States)

In this paper, we discuss the development of models for PZT bimorph actuators used to power micro-air vehicles including Robobee. Due to highly dynamic drive regimes required for the actuators, models must quantify the nonlinear, hysteretic, and rate-dependent behavior inherent to PZT in highly dynamic drive regimes. We first employ the homogenized energy model (HEM) framework to model the actuator dynamics. This provides a comprehensive model, which can be inverted and implemented for certain control regimes. We additionally discuss the development of data-driven models and focus on the implementation of a model based on a dynamic mode decomposition (DMD). Finally, we will detail attributes of both approaches for uncertainty quantification and real-time control implementation.

10165-10, Session 2

Energetics of domain structures and phase transformations in ferroelectric single crystals

Peng Lv, Christopher Lynch, UCLA (United States)

The behavior of relaxor ferroelectric single crystals is affected by their domain structure. This is particularly complex due to the relatively flat energy landscape in which minima correspond to various preferred polarization directions within a phase and to different phases. Construction of a Landau energy function that accurately describes the homogeneous material response in the presence of applied stress and electric field is the first step toward being able to construct a phase field model suited to studying the energetics of domain and phase boundary formation. These energy functions can be modified to capture the effects of compositional modifications and temperature and they can be used to simulate the evolution of domain structures. Our vision is that they will ultimately be able to guide the selection of composition that will lead to domain structures best suited for specific applications.

To date we have successfully constructed a 10th order Landau function for PIN-PMN-PT with composition near the morphotropic phase boundary that captures the temperature dependence of phase transformations, and matches the spontaneous polarization, the dielectric permittivity, and the electro-mechanical coupling. The field-driven phase transformations that occur when electric field is applied are also reproduced by this model. This includes the polarization and strain hysteresis loops.

We recognize that, at this point, we have fit a homogeneous model to measured heterogeneous material behavior. In future work we plan to implement this energy function in a phase field model to study the domain evolution in rhombohedral structures under external electric and mechanical boundary conditions. This will require modifications to the coefficients to account for the manner in which domain walls and phase boundaries reduce the energy barrier to domain switching and phase transformations.

10165-11, Session 3

Comprehensive modeling of a soft multiple-shape-memory polymer-metal composite actuator

Qi Shen, Tyler Stalbaum, Sarah Trabia, Taeseon Hwang, Robert Hunt, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

The multiple-shape-memory polymer-metal composite (MSMPMC) actuator can demonstrate complex 3D deformation. The MSMPMC have two characteristics, which are the electro-mechanical actuation effect and the thermal-mechanical shape memory effect. The bending, twisting, and oscillating motions of the actuator could be controlled simultaneously or separately by means of thermal-mechanical and electro-mechanical transactions. In our study, we theoretically modelled and experimentally investigated the MSMPMC. We proposed a new physical principle to explain the shape memory behavior. A theoretical model of the multiple shape memory effect of MSMPMC was developed. It is based on the assumption that the multiple shape memory effect is caused by the thermal stress and each individual Young's modulus is 'memorized' during the previous programming process. As the MSMPMC was reheated to each temperature, the corresponding thermal stress was applied on the MSMPMC, and the Young's modulus was recovered, which result in the shape recovery of the MSMPMC. Based on our previous study on the electro-mechanical actuation effect of ionic polymer-metal composite (IPMC), we proposed a comprehensive physics-based model of MSMPMC which couples the actuation effect and the multiple shape memory effect. It is the first model that includes these two actuation effect and multiple shape memory effect. Simulation of the model was performed using finite element method. To verify the model, a MSMPMC sample was prepared. Experimental tests of MSMPMC were conducted. By comparing the simulation results and the experimental results, both results have a good agreement. The current study is beneficial for the better understanding of the underlying physics of MSMPMC.

10165-12, Session 3

Influence of stress concentrations on failure of shape memory alloy actuators

Francis Phillips, Texas A&M Univesity (United States); Dimitris C Lagoudas, Texas A&M Univ. (United States)

Shape Memory Alloys (SMAs) are drawing much attention from the active materials community due to the solid-solid phase transformation which exhibits large actuation strains at large actuation stress levels. As SMAs become better understood, SMAs may become more commonly utilized as components of a system. Such systems would require SMAs to be attached to other components, often leading to a stress concentration at the attachment point. Therefore it is necessary to develop a more thorough understanding of how stress concentrations affect the failure in SMA actuators. One such stress concentration which is often encountered when attaching structural components together is a hole or notch. In this work, notched plates and notched cylindrical SMA specimens are investigated to elucidate how the notches affect the stress profiles and subsequent failure. Numerical results indicate that, while the presence of a notch may double the stress at the notch due to standard stress concentration effects, the phase transformation in an SMA leads to approximately a four-fold increase in stress at the notch tip during phase transformation in a thin plate. Furthermore, by changing the radius of the notch in cylindrical specimens, the evolution of the phase transformation is directly affected, which also impacts the distribution of stress along the area of minimum cross-sectional area. Experimental results are also presented, providing evidence that phase transformation in the presence of a stress concentration while at sufficient loads may lead to failure of the SMA.

10165-13, Session 3

Finite element analysis of iron-based shape memory alloy structures with heterogeneous stress and strain distributions under complex thermomechanical loading profiles

Cheikh Cisse, Wael Zaki, Khalifa Univ. of Science, Technology and Research (United Arab Emirates); Tarak Ben Zineb, Univ. de Lorraine (France)

This paper describes the phase transformation and plastic deformation in an Iron-based shape memory alloy (Fe-SMA) plate with a circular hole. The simulations were carried out using a nonlinear 3D model that considers both martensitic transformation and plasticity, as well as their coupling effects. The proposed model was developed within the framework of generalized standard materials with internal constraints and implemented in a UMAT. The state equations were derived from a thermodynamic potential corresponding to the Voigt mixture of the free energies of austenite and martensite, incremented with an interaction energy term. Despite being valid only for proportional loadings, the constitutive model is well-suited for FeMnSi SMAs wherein the martensite reorientation process is inexistent due to the high energy gap between variants. Using planes of symmetry, only quarter of the 20 x 10 x 1 mm plate subjected to an axial load of 200 MPa was analyzed. Simulations show that only phase transformation occurs at low temperature (20°C), only plastic deformation at high temperature (140°C), and both inelastic mechanisms at moderate temperature (60°C). Similarly to the stress distribution in a plate with central hole, concentrations of transformation and plastic strains were reported at the hole surface, perpendicularly to the loading direction, with the first strain type being recoverable after heating. Compared to linear elastic fracture mechanics, presence of martensitic transformation reduced nearly by half the stress intensity factor. This demonstrates the eligibility of the model for the design of Fe-SMA structures in complex service conditions.

10165-14, Session 3

Predictive modeling of actuation behavior of precipitation hardened high temperature shape memory alloys

Jobin K Joy, Alexandros Solomou, Texas A&M University (United States); Theocharis Baxevanis, Texas A&M Univ. (United States); Dimitris C Lagoudas, Texas A&M University (United States)

A finite element based representative volume element model for the prediction of the thermo-mechanical response of heat-treated NiTiHf SMAs is developed. Randomly placed precipitates are considered in material's matrix with eigenstrains corresponding to the lattice mismatch between the precipitates and the matrix are introduced into the precipitates to develop the coherency stress and strain fields. The development of the Ni, Ti and Hf concentration fields, as a result of the precipitation growth process, are modeled by adopting Fick's diffusion law. A spatial variation of material properties are considered based on the calculated concentration fields. Numerical results demonstrate the effect of precipitate's shape, volume fraction and coherency stresses as well as the effect of elemental depletion on the post-aged materials thermo-mechanical response.

10165-16, Session 3

Graphene based skins on thermally responsive composites for deicing applications

Christopher R. Bowen, Emily Glover, Nick Gathercole, Univ. of Bath (United Kingdom); Kris Seunarine, Chris Spacie, Haydale Ltd. (United Kingdom)

This work will demonstrate the feasibility of forming multi-functional graphene based surfaces capable of thermal heating for deicing applications. Graphene layers are deposited onto composite skin surfaces and used to melt the ice-skin interface by Joule heating while simultaneously developing a thermal strain in the skin structure to develop a shear stress to debond the ice-skin interface. The electrical properties, microstructure, processing parameters and electro-thermal response of the electrically conductive graphene layers are examined along with the change in shape of the composite structure with temperauture. Initial deicing tests are demonstrated. Application sectors for the multifunctional skins include exposed instrumentation housings, structural members exposed to extreme environments (such as wind turbines) and transport (aerospace). The opportunity to limit the extent of ice build-up on structures has broad application opportunities and enable light weight structures with reduced material costs and fuel saving for mobile applications and improved performance for instrumentation. The potential for the skin to act as a sensor is also discussed.

10165-17, Session 3

Optimal layout of SMA layers to avoid delamination in composite smart structures

Simone Cinquemani, Pouya Haghdoust, Nora Lecis, Antonietta Lo Conte, Politecnico di Milano (Italy)

Passive method is an efficient way to control the vibration of the systems. lightweight structures which can be severely affected by vibration has renewed the interest in development of passive vibration control. This work describes the design and optimization of a hybrid layered composite structure for the passive suppression of flexural vibrations in slender and

light structures. By combining the high damping functional properties of shape memory alloy with the mechanical properties of fiber reinforced polymers (GFRP), smart lightweight composites can be designed. [16-17]. Unlike previous studies on this subject in which SMA layers were fully distributed along the structure, here we propose optimized shape of these layers in order to use the less amount of material while having the same efficiency. This can certainly enable us to achieve improved characteristics like lower weight, while meeting the strength, stiffness and damping requirements. Optimal patterning of SMA layers with particular attention to its integration in the host composite will be investigated. CuZnAl is considered as high damping material because of its promising damping properties. The optimal design and patterning of CuZnAl layers with particular attention to the integration in the host composite will be investigated.

The work starts with developing an analytical method for evaluating the energy dissipation inside a vibrating cantilever beam based on the behavior of CuZnAl which was observed in experimental test. The analytical solution is followed by a shape optimization using genetic algorithm in order to minimize the SMA material layer usage while keeping the damping high enough. Delamination problem at SMA/GFRP interface was discussed according to preliminary pull-out experimental tests conducted at PoliMi. Eventually different configurations of the hybrid beam structure with different patterns of SMA layer are proposed and compared in the term of damping capacity.

10165-18, Session 4

Design and fabrication of materials and structures with negative Poisson's ratio and negative linear compressibility

Arash Ghaedizadeh, Jianhu Shen, RMIT Univ. (Australia); Xin Ren, RMIT Univ. (Australia) and Central South Univ. (China); Yi Min Xie, RMIT Univ. (Australia) and XIE Archi-Structure Design Co., Ltd. (China)

Materials and structures with auxetic and negative linear compressibility are of great potential to be used in many applications because of their uncommon mechanical deformation features. However, their design and manufacture are less studied as compared to other mechanical properties. The aim of this research is to explore several new approaches relating to the design and fabrication of cellular materials and structures with these two uncommon features. For most cellular materials and structures, these uncommon properties only exist for a limited geometric range. To begin with, the geometric limit of the microstructure of a 2D elastomer-based auxetic material was identified numerically through large deformation analysis. Within the geometric limits, a tuning method was developed further to control their mechanical properties with prescribed performance constrains. A metallic auxetic metamaterial was used as an example of the developed tuning approach and its effectiveness was validated by experimental results with specimens manufactured using 3D printing technique. To reduce the manufacture cost using 3D printing, a composite approach was proposed to manufacture these metamaterials. Several new cellular composite structures with negative linear compressibility composite structures were used as examples to demonstrate the effectiveness of the design approach. The test samples were manufactured using traditional composite method with low cost. These investigations mentioned above have clearly demonstrated the feasibility of designing and manufacturing of mechanical metamaterials using the presented approaches and laid the foundation for the expansion of their potential applications.

10165-19, Session 4

Development of polymeric Ron Resch origami pattern for damping applications

Hani E. Naguib, Mohamed Ali Emhmed Kshad, University of Toronto (Canada)

This study investigates the Ron-Resch origami pattern as a sandwiched core that can be used in damping and the energy dissipation applications. Ron-Resch origami pattern is characterized by its easy way to form dome shape, and its capacity to redistribute incoming forces and dissipate energy. This behavior achieved from the reentrant of the structure elements of the origami tessellation that fold when loaded and unfold when stretched, causing negative Poisson's ratio. The main concern of the study is the effectiveness of the Ron-Resch origami structures to dissipate the impact energy. The design utilizes high impact resistance polymeric material that allows flexible design, dimensional stability, and good surface quality. Compression and impact tests were conducted and then the results have been validated and discussed.

10165-20, Session 4

Oder-reduced analysis of piezoelectric metamaterial considering damping and resistance effect

Wangbai Pan, Guoan Tang, Fudan Univ. (China); Jiong Tang, Univ. of Connecticut (United States)

Piezoelectric metamaterial has excellent performance in elastic wave guiding and vibration attenuation within certain frequency range. The key units for piezoelectric metamaterial are LRC circuits, which induce local resonance. The dynamic feature of piezoelectric metamaterial usually can be analyzed by finite element method. However the degrees of freedom of model can be large due to complex configuration and distribution of metamaterial. This research proposes a model order reduction method to those substructures containing piezoelectric metamaterial. The damping of the structure and the resistance of circuits are both taken into consideration as to maintain the dynamic feature of substructures accurately. For those well-designed substructures with piezoelectric metamaterial, the order-reduced model can be directly assembled to other normal mechanical structure by any general finite element software, which will increase the analysis efficiency of entire structure. Case analyses are performed to verify the feasibility of reduction method.

10165-21, Session 4

Self-folding structure using light-absorption of polystyrene sheet

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The self-folding of polystyrene sheet can be realized by the localized thermal absorption in narrow area, and it is easily achieved by light and black-colored line pattern printing. Lighting to polystyrene sheet provides thermal energy stored in infrared ray to black-colored area except transparent area, then the polystyrene sheet near black-colored area becomes glass transition state. The extreme thermal contraction deformation at black area results in folding deformation of polystyrene sheet. In this paper, various self-folding structure using the light-absorption folding technique of polystyrene sheet can be designed and manufactured. For prediction of light-activated folding behavior of polystyrene sheet, the cohesive line element is employed. In the cohesive line element, the additional nodes are defined at folded line, and the discontinued folding angles can be identified and be analyzed from finite element analysis.

10165-22, Session 5

New sensing method of dispersion and damage detection of carbon fiber/polypropylene-polyamide composites via two-dimensional electrical resistance mapping

Joung-Man Park, Gyeongsang National Univ. (Korea, Republic of) and The Univ. of Utah (United States); Dong-Jun Kwon, Pyung-Su Shin, Jong-Hyun Kim, Gyeongsang National Univ. (Korea, Republic of); Lawrence K. DeVries, The Univ. of Utah (United States)

Carbon fibers are used as sensing elements in CFRP due to their electrical conductivity. In some more advanced studies, in CRFP, the carbon fibers were used for both strain sensing and damage sensing. The basic theory, in such studies, was that the movement of carbon fiber could be detected by ER (ER) measurement. This work evaluated the potential use of carbon fiber/polypropylene-polyamide (CF/PP-PA) composites in thermoplastic automobile applications. Two dimensional electrical resistance (2D ER) mapping was use to sense and predict damages. The extent of random dispersion of carbon fibers (CF) in PP-PA matrix was evaluated using 2D ER mapping contour charts. ER data collected at 9 different positions was used to evaluate dispersion and micro-damages. The uniformity of dispersion of CF in fractured surfaces was observed for comparison. Pyrolyzed specimens were used to measure CF amount in each part and compared with 2D ER mapping. The differences in ER for tensile and compressive stresses were compared to explore their usage for real time monitoring and sensing of damages. The observation of the fractured surfaces exhibited an acceptable consistency with 2D ER results. Ultimately 2D ER mapping should be useful for evaluating and predicting damages in CF/PP-PA composites under various loading conditions. This may have some very significant practical importance. It may point the way to use quick easy tests to screen and predict other mechanical failure behaviors for composites of different materials and/or processes. Perhaps a simple 2D ER mapping test might be used to predict and select good candidate materials, surface processing techniques for various high strength composite applications.

10165-23, Session 5

Development of carbon nanotube: cellulose composites using a simple papermaking process for multifunctional sensing applications

Sheila Goodman, Anthony B. Dichiara, Univ. of Washington (United States)

For more than 4000 years, paper has been mainly used for the purpose of recording information. With the recent advance in the field of flexible electronics and wearable devices, paper is being investigated as an environmentally friendly alternative to the traditional petrochemical-based polymeric materials. In this work, carbon nanotubes (CNTs) were employed as fillers to produce electrically conductive papers using a typical papermaking process. Lignin was utilized as a renewable dispersant to prepare aqueous suspensions of CNTs and softwood fibers, which served as precursors for sheet fabrication (60 g/m2). CNTs were functionalized to increase the presence of hydroxyl groups and further improve the interfacial strength between CNTs and cellulose fibers through hydrogen bonding. Both tensile strength and breaking length of the papers increased by more than 10% with volume resistivities in the range of 1,600 Ω.cm for CNT loadings as low as 2.5 wt%. The multifunctional sensing behavior of the composite papers to aqueous solutions and tensile strain was thoroughly studied. Results show that the relative electrical resistance significantly increased under water and returned almost to their initial levels after drying, with fast and reproducible signals over multiple immersion/drying cycles. The piezoresistive behavior of the composites increased linearly at low strains followed by an exponential growth at larger strains, and exhibits higher sensitivity than conventional strain gauges. These novel CNT-cellulose composite papers have outstanding multifunctional properties and are promising to be employed for the design of various smart materials, which can revolutionize the way electronic devices are manufactured and used.

10165-24, Session 5

Electrochemical and mechanical properties of a PEG based solid polymer electrolyte for power storage composites

Constantin Ciocanel, Cindy Browder, Gerrick Lindberg, Northern Arizona Univ. (United States)

Development of multifunctional materials with power storage and structural capabilities poses many challenges, of which the formulation of a solid polymer electrolyte (SPE) with adhesive like properties may be the greatest. This is due to the targeted properties of the SPE, i.e. high ionic mobility combined with high mechanical strength and good adherence to multiple substrates, which are all mostly divergent. To date, gel electrolytes have been used to prove the feasibility of power storage flexible materials. However, mechanically, these materials do not exhibit notable properties. This presentation will discuss the development process and electrochemical and mechanical properties of a PEG based SPE and highlight the remaining challenges to be surmounted for the successful development of a true structural composite material with power storage capabilities.

10165-25, Session 5

New conductive and high energy density air-cathode made of carbon fiber and carbon nanotubes buckypaper for electrically rechargeable zinc-air batteries

Arturo Reza Ugalde, Univ. of Toronto (Canada); Hani E. Naguib, Univ of Toronto (Canada)

Metals-air batteries have been on the spotlight as the next generation of energy storage systems due to the high energy density in comparison with li-ion batteries. Since primary batteries made of zinc and aluminum already reached high electrochemical performance and also have the advantages of high recyclability, low cost and also are safer for user's interaction, their feasibility as energy suppliers for portable devices has growth considerably, focusing wider research on the development of high efficiency rechargeable zinc-air batteries. This study presents the analysis and electrochemical tests of a new conductive and high energy density air-cathode made of a thin film of aligned carbon fiber as oxygen diffusion layer and a carbon nanotubes buckypaper as oxygen reduction reaction and oxygen evolution reaction bifunctional catalyst for electrically rechargeable zinc-air batteries with high strength and flexibility.

CNTs-buckypaper presents good mechanical and electrochemical properties, the natural porosity allows good oxygen diffusion and catalytic activity for both ORR and OER whereas the carbon fiber film, acts as conductive and hydrophobic permeable oxygen diffusion layer. Their electrochemical performance is tested and discussed.

10165-26, Session 5

Development of eletrothermal actuator (ETA) with biodegradable polymeric matrix for artificial muscle applications

Yu-Chen Sun, Univ of Toronto (Canada); Benjamin Leaker, Univ. of Toronto (Canada); Hani Naguib, Univ of Toronto (Canada)

Electrothermal actuators (ETAs) are novel active materials that can generate different kinds of motions by thermal expansion induced from Joule heating. The degree of expansion, which influences the deformation and response force, is determined by the coefficient of thermal expansion (CTE) of the material. In order for the material to be activated, it is necessary to create conductive network for Joule heating to take place. As a result, one of the most common methods for creating ETAs is to insert high electrical and thermal conductive filler into the matrix, which allows for fast and uniform heat distribution though out the material, thus initiate the actuation. In this study, we present the characterization results of newly developed ETA composites fabricated from a novel biocompatible polymer, poly(glycerol sebacate) (PGS). It was suggested that the elastomer-like PGS can be used in mimicking human tissue due to its distinct mechanical properties. The matrix can be prepared by crosslinking sebacic acid to glycerol using a simple technique with high production rate. To create the novel ETA composites, uncured PGS solution is coated to conductive networks which are constructed from high electrical conductive fillers such as carbon nanotubes. The actuation performance of the novel ETA composites is characterized in terms of its blocking force, maximum displacement and the reaction time.

10165-27, Session 6

The effect of nano fillers on the polymerization shrinkage kinetics and mechanical behavior of composites

Ermias G Koricho, Georgia Southern University (United States); Anton Khomenko, General Photonics Corporation (United States); Mahmoodul haq, Michigan State University (United States)

The main objective of the present study was to investigate the effect of nanoclay reinforcement on time-dependent volumetric shrinkage of three epoxy resins during polymerization and associated change of mechanical properties of the resulting composite materials. The materials used in this work were two part epoxies from Applied Poleramics Inc., namely, ER3/EH103, ER10/EH103, and DR5/EH103.

Conventional methods which utilize 1D and 2D strains measurement are highly dependent on boundary conditions and can be used only for approximation of volumetric measurements. In order to measure the volume directly and monitor time-dependent shrinkage during the polymerization process, the Accupyc II 1340 gas pycnometer with Peltier controller was used. The materials were cured in-situ in the pycnometer chamber at 49 °C for 4 h followed by a post cure of 4 h at 65 °C. Time-dependent shrinkage of individual resins was monitored through continuous volumetric measurements during the entire curing cycle. On the other hand, the tensile specimens were cured in the conventional oven using the same curing cycle. Experimental results showed that depending on the epoxy and nanoclay concentration, variation in time-dependent shrinkage was observed relative to pristine epoxies. Besides, inclusion of nanoclay has shown considerable change in mechanical properties of the composite material.

Although such observations were expected, detailed quantification on the volumetric shrinkage with a new technique and its effect on structural components made of such resin are not well documented. Overall, the study lays the groundwork for understanding shrinkage induced effects on strengths of resin/adhesive dominant structural components.

10165-28, Session 6

Bistable morphing composites with selectively prestressed laminae

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Bistable laminated composites are candidates for morphing structures since they are capable of large deflections without actuation and can exhibit drastic shape change when actuated. The coupled stable shapes of traditional thermally-cured fiber-reinforced polymeric laminates are the result of a globally-prestressed matrix and hence cannot be tailored independently. In this paper, we address this limitation by presenting an equivalent laminated composite in which mechanical prestress is applied to the matrix of selective laminae to achieve bistability; shapes are tailored individually by changing the magnitude of prestress in each lamina. The application of mechanical prestress is associated with an irreversible non-zero stress state which when combined with smart materials with controllable stress-states results in multifunctional morphing composites.

The proposed bistable composite consists of a core that is sandwiched between two prestressed laminae. Fiber-reinforced elastomers, also known as elastomeric matrix composites (EMC), are used as prestressed laminae as they are capable of anisotropic strain. In a 900 EMC/core/00 EMC configuration, the stable shapes of the composite are shown to be weakly-coupled where each curvature depends only on the prestress in the EMC on the concave face.

The composite is modeled analytically using classical laminate theory and Von Karman's hypothesis for laminated plates; geometric and material nonlinearities related to large prestrain in the elastomer are included. A parametric study of the effect of core properties, laminate size, and aspect ratio on composite curvature is presented. Samples of bistable laminates are fabricated in various configurations for testing and model validation. The shapes of the composite, measured using a motion capture system, are found to be in agreement with the simulated shapes.

10165-29, Session 6

Strain-dependent and hysteretic resistance of stretchable carbon nanotube networks

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The increasing demands of human-machine integration require stretchable electronic devices. Percolating networks of carbon nanotubes (CNTs) have potential to work as stretchable electrodes and semiconductors, since CNTs can reorient and slide under large deformation. In this work, we investigate the effect of cyclic loadings on the resistance and morphology of stretchable CNT electrodes, by combining experiment, coarse grained molecular static (CGMS) simulation, and analytical modeling. Experimentally, a CNT electrode spray-coated on the surface of a stretchable substrate is subject to cyclic stretches with the maximal strain sequentially increasing. The resistance of the electrode in both stretching and transverse directions increases during the loading, while it remains almost a constant during the unloading, forming a hysteresis between the loading and unloading. To understand the strain-dependent and hysteretic resistance of stretchable CNT electrodes, we have developed a CGMS method to simulate the morphological change of CNT networks under cyclic loadings. Then we calculate the evolution of the resistance for different CNT configurations, by modeling a network of nanotube resistances and contact resistances. We find that during stretching, the CNTs reorient to the stretching direction. As the strain increases, the nanotubes slide between each other, and the resistance of the network increases. During the unloading, the CNTs buckle due to the compression, and the resistance of the network remains almost a constant. Based on this understanding, we have further developed an analytical model to describe the evolution of the resistance of CNT electrodes under arbitrary loadings. This combined approach enables us to design stretchable CNT devices with optimized properties.

10165-30, Session 6

Design of thermally adaptive composite structures for damping and stiffness control

Pauline Butaud, Gael Chevallier, Morvan Ouisse, Emmanuel Foltete, FEMTO-ST (France)

Viscoelastic materials are widely used to control vibrations. However, their mechanical properties are known to be frequency and temperature-dependent. Thus, in a narrow frequency bandwidth, there is an optimal temperature that corresponds to a maximum loss factor and it is tricky to get a high damping level over a wide frequency range. Furthermore, an optimal temperature for a maximum structural damping leads to a poor static stiffness because the peak of the loss factor is obtained during the glass transition when the storage modulus is decreasing. Additionally, in industrial applications, the requirements might change according to the system lifecycle. For instance, the stabilization functions that are used for optronics applications require high stiffness for positioning steps, and high damping for filtering functions. To achieve this goal, engineers usually use several viscoelastic materials with functionally graded damping properties. This allows obtaining a high loss factor over a wide frequency range. This solution is however not adaptive. In order to be able to adjust the properties in real time, we suggest in this paper to use a single material which properties are functionally graded thanks to a non-uniform temperature field over the structure. The resulting composite structure is based on a bio-compatible viscoelastic shape memory polymer whose properties are tailored with the temperature field. A composite structure has been designed integrating a viscoelastic core and a heat control device. The optimal temperature field has been obtained through the minimization of a cost function that reflects the compromise between structural damping over a wide frequency band and high static rigidity.

10165-31, Session 6

Stress-strain and fracture toughness behaviour of composites reinforced with inhomogeneously distributed particles

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Different failure mechanisms determine fracture toughness of particle composites as, for example particle debonding and ductile matrix fracture. In real composites the particles are not homogeneously distributed. This leads to different levels of particle interaction under loading and consequently to higher stress concentrations in the matrix and at the particle/matrix interface for closer particles. This local inhomogeneity is modelled and the effect on stress-strain behaviour is discussed.

The variation of stresses in front of a crack effects the stress concentration in the neighbourhood of the local inhomogeneously distributed particles. This effect is considered for the modelling of fracture toughness of such composites. The influence of the pair distribution function on the debonding energy and on fracture toughness as a function of particle volume fraction is discussed.

10165-32, Session 6

Influence of heating time of pyrolysis method for extracting recycled carbon fibers from wasted Prepreg on fiber breakages in its injection molded composite

Koki Itokawa, Kazuya Okubo, Toru Fujii, Doshisha Univ. (Japan)

The purpose of this study is to investigate the influence of heating time of pyrolysis method to extract recycled carbon fibers from wasted Prepreg on the fiber breakages in injection molding process making its composite. It was found that extended time of pyrolysis method reduced the strength of single recycled carbon fiber and then the length of remained fiber in the molded composite, since lots of flaws were initiated on the surface of carbon fibers in extraction process.

10165-33, Session 6

Impact resistant smart hybrid laminates

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

The large diffusion of structural parts made of carbon fibres reinforced polymers (CFRP) in the aerospace and automotive sector has highlighted the importance of developing hybrid multifunctional materials characterised by improved mechanical properties and coupled with non-structural features. Indeed, while due to their high specific strength and light weight, composite systems are characterised by very high mechanical properties in the in-plane direction, their intrinsic layered structure makes them very susceptible to low-velocity impacts resulting in Barely Visible Impact Damage (BVID) that can lead to the critical failure of primarily structures. Based on these premises, the development of a multifunctional hybrid system can overcome this drawback by tackling this issue from two different points of view, enhancing the total reliability of light-weight composite parts in order to improve fuel efficiency and optimise the footprint of the new generation aero-structures. Indeed, by including an additional metallic phase within the structure of a traditional laminate it is possible to develop a smart multifunctional system in which the hybrid phase acts simultaneously as a reinforcement to enhance the out-of-plane properties of the material and as an intelligent embedded sensor system able to communicate information about the health status of the part and detect impact events or critical loads.

This work is focused on the design, manufacturing and testing of an H-CFRP in which the hybridisation in obtained by including an array of Shape Memory Alloys or Copper wires within the laminate. The electrical properties of the hybrid network is exploited to design a smart sensing system which can be interrogated to monitor the load distribution on the part and detect critical solicitations in critical points. The low-power system, controlled by an Arduino modulus, is able to monitor the integrity status of the part using each wire as a linear probe to scan complex structures at a certain frequency, measuring the local change in the electrical resistance from which it is possible to build a map of the stress distribution. The position of the metallic network along the laminate's thickness was determined by analysing the response of different configurations of hybrid samples subjected to low velocity impacts (LVI) in order to optimise the design of the H-CFRP and enhance the energy absorption. The extent of the internal delamination generated by the impact was then assessed by exploiting the hybrid phase as an embedded heat source and monitoring the variation of the superficial apparent thermal variation with an Infra-Red (IR) Camera. The results were compared with traditional techniques (phased array and c-scan) and proved the effectiveness of the hybrid phase in increasing impact resistance and reducing the dimensions of the delaminations.

10165-34, Session 6

Multifunctional surfaces produced using fiber debonding and pullout in composite materials

Reza Rizvi, The Univ. of Toledo (Canada); Ali Anwer, Hani E. Naguib, Univ. of Toronto (Canada)

This paper details the development of compliant textured surfaces based on fibrous composites that possess enhanced hydrophobic surface wetting properties. The fibrous composites consist of various micro-fiber phases

reinforcing a compliant elastomeric matrix. The fiber phase is textured such that it is aligned transversally and protruding out of the elastomer surface. This is achieved by mechanically cutting and rearranging a longitudinally aligned molded composite – a process that takes advantage of the fiber debonding and pullout phenomenon. The textured surface brought about by the aligned and protruded fibers is apparent in both the surface morphology and metrology of the composites. Contact angle wetting studies indicate that the fiber protrusions enhances the hydrophobicity of the surface. A maximum contact angle of 110° is observed with a carbon fiber content of 16vol%, representing a 32% improvement in the surface hydrophobicity over unreinforced TPU (84°). The textured fiber composites in this study represent a facile method to enhance the multi-functionality of composites, by imparting hydrophobic behavior, without the need for any additional surface coating or post-process texturing.

10165-49, Session PMon

FEM simulation and experimental measurement of hardness by the Superficial Rockwell HRT scale using the steel and tungsten carbide spherical indenters

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This paper considers the comparison and evaluation of Superficial-Rockwell (HRT) hardness tests using the steel and tungsten carbide ball indenters. There are differences observed in Superficial-Rockwell HRT hardness scale tests by using 1.588 mm (1/16") diameter steel and tungsten carbide ball indenters. The modeling was made with HRT hardness reference blocks and widespread soft thinner gage material (steel, copper, aluminum, and duralumin). In the simulation determined that the tungsten carbide indenter balls have the advantage of being less likely to flatten with repeated use and the use of hard metal ball indenters may have different measurement results than tests using steel ball indenters. The simulation of indentation process are performed by the finite element method in the Academic version of ANSYS software product, which is available for free use on the website The simulation results are confirmed by experimental studies. For further analysis of the results of comparisons it is interesting to conduct researches for micro-Vickers scale. Furthermore, the practical application of the obtained results allow to evaluate the quality abradable surfaces in the design of structural components with small clearances. The obtained results are important for evaluation of the results of international comparisons of the national standards. This work was performed as part of preparation the Draft A COOMET.M.H-S3 - Supplementary comparison of regional metrological organization for Superficial-Rockwell Hardness scales.

10165-50, Session PMon

Parameter influence on tensile properties of scarf-repaired composite laminates

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A finite element model of scarf repaired composite laminates in tension is built in this paper based on FEM software ABAQUS. The ultimate strengths of the repaired structures are calculated with progressive damage analysis method which can effectively analyze the damage formation and evolution of repaired composite structures. The predicted results agreeing well with the experimental results which means the model is reliable. The failure model of these structures is adhesive failure which is obtained by analyzing the failure process of these structures increasing in tension.

The effects of scarf ratio and scarf depth on the ultimate strengths are obtained by analyzing the simulation results of scarf repaired composite laminates under different scarf ratios and scarf depths .The results show: First, the stress distribution becoming more uniform which contributes to the delay of adhesive damage so that the ultimate strengths are improved with the decreasing of scarf ratio; Second, when the scarf depth is large, decreasing the scarf depth can increase the ultimate strengths of the repaired structures which is caused by two parts: the adhesive damage becomes smaller with the scarf depth is decreased under the same strength and the strength of intact ply is bigger than that of repaired ply. when the scarf depth is small, the failure model of the repaired structure changes to motherboard failure and the ultimate strength of the repaired structure is close to that of intact structure .The results of this study can provide some references for the design of scarf repaired composite laminates.

10165-51, Session PMon

Application of the FEM for modeling and prediction of the relationship between the hardness and stress of the deformed body

Volodymyr V. Skliarov, Jakov Dovzhenko, National Scientific Ctr. "Institute of Metrology" (Ukraine); Maxim Zalohin, Kharkiv National Automobile and Highway Univ. (Ukraine)

A plastic deformation of the metal significantly changes its internal structure and greatly influences many mechanical, physical and chemical properties. In the plastic deformation process, electrical resistance increases, magnetic properties change and thermal conductivity and workability of metal decrease. But this influence is especially evident in the measurement of the hardness of the deformable body, which is directly related to an increase in the yield strength of the material, i.e. to its hardening. Hardness measurements were conducted on the unbroken samples over the entire length. After the experimental study on samples rupturing, repeated measurements of hardness over the entire length were carried out. Modeling of the process of samples rupturing was carried out by finite element method in Academic version of ANSYS. The analytical link between the calculated and experimental values of hardness and stress state of the sample was determined. The obtained results are important for evaluation of the results of international comparisons of the national standards of hardness. As the perspective directions for the practical application of the results, evaluation and prediction of hardness of the hardness standard measures of the first grade during their manufacturing process were proposed. The predictions of the FEM models were compared with experimental data, and the accuracy of these predictions was quite satisfactory.

10165-52, Session PMon

Comparative study on corrosion characteristics and mechanical properties of zinc-aluminum-alloy coated and zinc-coated high strength wires in stay-cables

Yang Xu, Harbin Institute of Technology (China); Fujian Zhang, CCCC Highway Consultants Co., Ltd. (China); Shunlong Li, Harbin Institute of Technology (China)

A comparison study on corrosion characteristics and mechanical properties of zinc-aluminum-alloy coated and zinc-coated high strength wires was conducted. Uniform corrosion depth was calculated to evaluate the corrosiveness, and tensile and fatigue tests were carried to assess the mechanical performance of corroded wires. SEM and EDS analysis were adopted to the corrosion products under different corrosion periods. The measured uniform corrosion depth followed a lognormal distribution, and corrosion speed changed from the coating to the steel corrosion stage.

Results showed that the zinc-aluminum-alloy coat of high strength wires had a better resistant to salt spray corrosion than the zinc one.

10165-53, Session PMon

Development and characterization of novel light-curable composites with calcium phosphate silicate

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Dental composite resins are the main direct tooth restorative materials. The more recent research and development efforts on dental composite resins focused on developing adequate strength, high wear resistance and low shrinkage. Polymerization shrinkage and its accompanied stress may destroy the composite/tooth interfacial bond and lead to recurrent caries. In this paper, novel light-curable composite resins with tricalcium silicate (C3S) and calcium phosphate monobasic (CPM) were synthesized. C3S hydrates to produce calcium silicate hydrate (C-S-H) gel and calcium hydroxide (CH) which accompanied volume expansion. Polymerization shrinkage of dental composite resins with C3S fillers were compensated and improved. CPM reacts with the CH to precipitate hydroxyapatite (HAP) in situ within C-S-H which can largely remove CH to enhance the biocompatibility and bioactivity of composites. As the main component of bone and tooth, the precipitate HAP has the potential to remineralize tooth and inhibit caries. FTIR, SEM, XRD, DSC were used to characterize the microstructures of dental composite resins. Chemical-physical properties were assessed include mass and volume change, polymerization shrinkage, mechanical properties, water adsorption, ion release and remineralization properties. The results showed that the novel composite resins in oral environment had volumetric expansion to compensate shrinkage owing to hydration effect. They also had remineralization potencial and competitive mechanical properties.

10165-54, Session PMon

High performance microwave absorption of the arc-discharge carbon nano onions

Chao Ruan, Yanju Liu, Jinsong Leng, Zhichun Zhang, Liwu Liu, Harbin Institute of Technology (China); Yongfu Lian, Heilongjiang Univ. (China)

The onion-type nanostructure of polyhedral carbon nano onions (CNOs) and core-shell interfacial nanoarchitecture of metal encapsulating CNOs become very promising candidates for high performance microwave absorption due to their outstanding dielectric properties and compatible dielectric loss and magnetic loss abilities. In our lab, raw soot containing carbon onions were prepared by traditional arc-discharge process using composite graphite rod as both carbon sources and catalyst. The impurities ranging from residual metallic catalysts to amorphous carbon, carbon nanotubes and large nano-graphitic debris were sufficiently removed through successive ignition, acid wash, surfactant-assisted dispersion, and filtration as reported in our previous work. Both the raw soot and purified CNOs present a typical cloaking feature originated from the superior electromagnetic wave absorption. We believe that such high performances are aroused from the onion-type configuration and core-shell interfacial architecture at nanoscale, which could provide desirable impedance match, thus indicating that the raw soot and purified CNOs can be applicable in the field of microwave absorption.

10165-55, Session PMon

The photonic crystal laser based on the silica opal structure filled with dye doped photoresist

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Photonic crystal (PC) is proposed as special structure in 1990s, which has optical phenomena called photonic band gap (PBG). For the PBG, the specific wavelength of light will not be allowed to transmit through the PC, but can be diffracted in the PC structure as the Bragg's diffraction. The structure of PC can be fabricated by the nanotechnologies, such as self-assembly, E-beam, and lithography. However, the self-assembly is most simple and low-cost method.

In this study, a photonic crystal laser based on the silica opal structure filled with dye doped photoresist has been proposed. The mono-dispersed silica particles are fabricated by the Stöber process, and the diameter of the silica particles can be controlled by the concentration of TEOS in the reaction. The different locations of PBG in the PC (or opal) structure can be formed by the self-assembly with various sizes of silica particles, and then calculated by the Bragg's diffraction theory. The PC laser is fabricated by the dye R6G doped with negative photoresist SU-8 (as the gain medium) filled into the voids of the opal structure (as the cavity). After the irradiation of Nd:YAG pulsed laser, the fluorescence can be generated and accumulated on the PBG's edges of the opal structures resulting in the lasing of the PC laser. The lasing wavelength of the PC laser can be further adjusted by changing the filling materials or the PBG of the opal structures.

10165-56, Session PMon

Deformation characteristics of CFRP bi-stable composites according to negative initial curvature

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In this paper, deformation characteristic of CFRP laminated composites according to negative initial curvature is discussed, and twisted shape bi-stability of CFRP composites is introduced. Initial curvature of composites has effect on final curvature of bi-stable composites. Positive initial curvature tailor final curvature linearly. However, some negative initial curvature induces twisted shape bi-stability. CFRP laminated composites have three different final state (i.e. conventional shape bi-stability, mono-stability, and twisted shape bi-stability) according to initial curvature. Twisted shape bi-stable composites have different curvature changing characteristic from conventional shape bi-stable composites. In order to analysis effect of initial curvature, analytical model that include force and moment equilibrium is proposed. FE simulation results and analytical results are compared to verify the proposed analytical model. It is verified that some range of negative initial curvature induce losing of bi-stability or twisted shape bi-stability by analytical model. Final state shape of three different state is analyzed by FE simulation and analytical model. Final states shape from two different analyses are well matched each other in three different state.

10165-57, Session PMon

Scanning thermo-ionic microscopy

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Traditional electrochemical characterization microscopy methods based on charge measurement do not provide nanometer spatial resolution. The recently developed electrochemical scanning microscopy (ESM) which is based on atomic force microscopy (AFM) provides nanoscale measurements, however, the electrochemical measurements consist of other effects such as electromechanical and electrostatic effects.

We developed a scanning thermo-ionic microscopy (STIM) to probe local electrochemical activities at the nanoscale regime. The microscopy mechanism is based on imaging the Vegard strain induced by thermally driven stress and temperature oscillation. The Vegard strain linearly correlates with material lattice constant and can be used as a measure of ionic species concentration. Through theoretical analysis and experimental validation, we have demonstrated that second and fourth harmonic components of the AFM deflection signal contains information about species concentration. It is demonstrated that the second harmonic response predominantly correlates with the local thermal expansion information, while the fourth harmonic one is characteristic of local transport activities that is presented only in ionic systems. All our measurements are resonance enhanced and since the tip-sample resonance varies during scanning, four lock-in units and a PID controller are integrated with the AFM to track the resonance frequency. The technique has been applied to probe Sm-doped nanocrystalline Ceria and $LiFePO_4$, both of which exhibit higher STIM amplitude near grain boundaries as expected.

The STIM is an innovative tool to study local electrochemistry with high sensitivity and spatial resolution for a wide range of systems, without any electrical cross-talk which makes it suitable to be applied in operando.

10165-35, Session 7

Rheological properties of eutectic gallium-indium alloy liquid metal as a smart self-healing material

Carleen Bowers, Jennifer Lalli, Richard O. Claus, NanoSonic, Inc. (United States)

This work investigates the rheological behavior of eutectic gallium-indium alloy (EGaIn)—an electrically conductive liquid metal—as a promising smart self-healing material for the autonomous sensing and repair of damaged conductive materials and electronic devices. EGaIn is liquid at room temperature and spontaneously forms a thin skin (~0.7 nm) in air (or other oxidizing environments), which consists predominately of gallium oxide (Ga_2O_3). This surface oxide is smooth, elastic, and electrically conducting. Due to the presence of the elastic surface oxide, EGaIn has unique rheological properties at room temperature that make it especially suitable for self-healing. The application of a critical surface stress causes the oxide to rupture and the internal liquid metal to flow to points of damage, where it is re-oxidized in air or other oxygen-containing environments. Using a rheometer with a parallel plate geometry, we investigate the flow properties of EGaIn without a surface oxide and EGaIn with increasing thicknesses of the surface oxide. Increasing the thickness of the oxide increases the critical stress required for rupture. We also demonstrate the i) fabrication of smooth nano- and microscale particles of EGaIn using shear forces and ii) the incorporation of the particles in thin-film composite materials.

10165-36, Session 7

NDE of smart rheologically recoverable self-healing and radiation shielding materials

Jennifer Lalli, NanoSonic, Inc. (United States); Gerard Valle, NASA Johnson Space Ctr. (United States); Carleen Bowers, Vince Baranauskas, Keith Hill, Richard O. Claus, NanoSonic, Inc. (United States); Thomas Borak, Colorado State Univ. (United States)

In a recent study with NASA, NanoSonic has designed and produced a multifunctional low air permeable, cryogenically flexible, self-healing material as a candidate bladder for space inflatables. NanoSonic's innovative self-healing mechanism is accomplished rheologically, rather than chemically, which allows for immediate self-sealing under reduced pressure and thus, potentially in space. The overall composite design consists of a space radiation resistant fiber reinforced, low glass transition temperature (Tg), -90 F polymer, rheologically recoverable self-sealing polymer gel, and low Tg abrasion resistant polymer topcoat. A materials radiation durability study was conducted on these smart materials with NASA JSC / Brookhaven National Laboratory National Space Radiation Laboratory and Colorado State University. Materials were subjected to 50-year simulated solar particle event (SPE) and galactic cosmic ray (GCR) radiation under a dose of 10,300 cGy with 24.3 MeV proton, and 709 cGy 1 GeV proton, Fe, and proton/Fe, as well as irradiation with a high dose of 600 Gy with 18 MeV electrons. It was found that these lightweight (0.92 g/cc) composites maintain low air permeation before after repeated cryogenic flexure at -50 C, and upon simulated space irradiation. The composites also self-seal and maintain pressure at 8 psi, after repeated punctures with a 2 mm probe, and after repeated cryogenic flexure. The smart composites exhibits an increase in mechanical strength (when tested at -45C, 23 C, and 90 C) with minimal loss in elasticity, post simulated GCR and SPE exposure, suggesting a reasonably tough material.

10165-37, Session 7

3D printed thermoplastic polyurethane with isotropic material properties

Cameron J. Hohimer, Josef F. Christ, Nahal Aliheidari, Changki Mo, Amir Ameli, Washington State Univ. Tri-Cities (United States)

Fused Deposition Modeling (FDM) is becoming increasingly popular due to its high versatility, high design flexibility, and relative low cost. Of interest in the FDM field is thermoplastic polyurethane (TPU) as its elastomeric properties can be exploited to create functionalized co-polymers and printed into strain gages and sensors for soft-robotic applications. Unlike rigid thermoplastics, the mechanical properties of flexible filaments like TPU have not been widely studied.

This paper investigates the mechanical properties of TPU parts created by a typical low cost desk-top FDM machine. TPU was first extruded into filament suitable for FDM and printed into samples for tensile tests according to the ASTM 3039 standard. The raster orientation, print temperature, and print speed were varied and tensile strength results compared to that of molded bulk TPU samples. While the printed samples had an overall lower ultimate tensile strength compared to the bulk samples, the printed samples showed nearly isotropic material properties across varying raster orientations. These results run contrary to that of similar studies on rigid FDM thermoplastics. It is hypothesized that this is likely due to the low glass transition temperature of TPU which allows the interlayer bonding between the print lines at even much lower temperatures.

10165-38, Session 7

The impact of nozzle and bed temperatures on the fracture resistance of FDM printed materials

Nahal Aliheidari, Washington State Univ. Tri-Cities (United States); Rajasekhar Tripuraneni, New Jersey Institute of Technology (United States); Cameron J. Hohimer, Josef F. Christ, Amir Ameli, Washington State Univ. Tri-Cities (United States); Siva Nadimpalli, New Jersey Institute of Technology (United States)

Additive manufacturing (AM) refers to a new technology in which physical parts are directly produced from a CAD model by incremental addition of the constituent materials. Fused deposition modeling (FDM) is one of the most common types of additive manufacture processes. The ultimate mechanical performance of FDM printed parts is governed by the quality of the interlayer bond. Current literature however focuses only on the phenomenological evolution of standard mechanical properties (such as tensile and bending) as a function of printing conditions. Such studies do not provide direct information about the interlayer adhesion. In this work, a fracture-mechanics-based methodology was established to measure the fracture resistance of FDM 3D printed ABS samples. Double cantilever beam (DCB) specimens was printed in such pattern that the applied load exerted only tensile opening stresses at the crack front. This facilitated the measurement of crack growth under pure mode-I condition. A finite element model was used to obtain the J-integral strain energy release rate values, as a measure of the fracture resistance. Since the crack propagated at the interlayer in all the cases, the fracture resistance was a direct indication of the interlayer adhesion. The results revealed that a maximum fracture resistance (or maximum interlayer adhesion) could be obtained at an optimum nozzle temperature while the fracture resistance (and interlayer adhesion) continuously increased with the bed temperature. This work provides insight into the relationship between 3D printing conditions and the resultant interlayer adhesion, which is of great importance in structural applications.

10165-39, Session 8

On the electric and magnetic alignment of magnetoactive barium hexaferrite-PDMS composites

Md Abdulla Al Masud, The Pennsylvania State Univ. (United States); Corey Breznak, Paris von Lockette, Zoubeida Ounaies, Pennsylvania State Univ. (United States)

This paper demonstrates how to judiciously use two different external fields to engineer a composite that responses to both electrical and magnetic fields. Specifically, the purpose of this study is to electrically and magnetically align M-type Barium Hexaferrite (BHF) in polydimithylsiloxane (PDMS) to obtain an orthotropic composite whose strength, stiffness and electrical and magnetic properties depend on the orientation of the BHF. First, the BHFs are successfully dispersed in PDMS by polyethylene glycol (PEG) surface modifier, heptane and probe sonication. Then they are electrically aligned in the polymer matrices by applying an AC electric field. From optical microscopy (OM) image assessment, the best alignment is achieved at 2 kV/mm and 1 Hz. Under the electric field, BHFs are found to rotate in the direction of the electric field and before coalescing form chains in the silicone elastomer. After the composite is electrically aligned and partially cured it was put under 0.76 Tesla permanent magnets. Under the magnetic field, BHFs were further aligned in plane and out of plane along their magnetic c axis within the chains that were formed while electrical aligning. After fully curing, the SEM results show parallel chain formation of BHFs as a sign of electrical alignment. Vibrating Sample magnetometer (VSM) and XRD results confirm BHFs are crystallographically aligned along their magnetic c-axis. The textured BHF-PDMS composites are found to have excellent anisotropic magnetic, dielectric, and mechanical properties.

10165-40, Session 8

Magnetoelastic shockwave response: experimental and numerical analysis

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Hypervelocity impacts generate shockwaves causing catastrophic damage and failure of surrounding material and structures. Adaptive materials have been previously studied to mitigate shockwaves by providing diagnostics tools, wave steering, and dissipating mechanical energy. Numerous ferroelectric studies have been conducted, with less focus on ferromagnets, or magnetoelasticity. This presentation explores the response of magnetoelastic Galfenol ($Fe_{81.6}Ga_{18.4}$) to high strain-rate, high stress amplitude loading.

Experimentally, 2 GPa rarefacted shockwaves are generated in Galfenol using a Nd:YAG laser. Magnetization changes are recorded using inductive coils along the sample length and interferometry is used to infer the stress amplitude at the specimen's back surface. The experimental results highlight how the shockwave evolves as it travels, including the onset of lateral release waves. Magnetic field control of the mechanical wave speed by 20% is observed, accompanied by large control of the measured magnetization changes. These changes highlight the coupled magnetoelastic nature of the effect. Furthermore, it is observed that the magnetization more strongly couples to lateral release waves than the incident compressive pulse. Last, magnetization changes are seen to precede the propagating mechanical wave, indicating dipolar coupling can transfer energy ahead of the mechanical wave front.

A numerical model has been developed to provide further insight into the experimental study. This model fully couples elastodynamics with magnetostatics using a nonlinear magnetoelastic constitutive behavior. The nonlinear model captures the main findings of the experimental study, including wave evolution, and strong magnetoelastic coupling to the release waves.

10165-41, Session 8

Rate dependence and shape memory effects in azobenzene polymers

William S. Oates, Sadiyah S. Chowdhury, Matthew Worden, Dennice Roberts, Florida State Univ. (United States)

Polyimide-based azobenzene polymer networks have demonstrated superior photomechanical performance over more conventional azobenzene-doped pendent and cross-linked polyacrylate networks. Here we develop a constitutive modeling framework and experimentally quantify both the photomechanical and theromechanical coupling in these materials. The rate dependent deformation induced by these two effects is quantified experimentally through photomechanical stress measurements and infrared camera measurements. The results are compared to a model that includes both rate dependent deformation as a function of the optically active azobenzene molecules, coupling to the polymer network viscoelasticity, and thermal expansion.

10165-42, Session 8

Programmable bending of liquid crystal polymer strips by light and heat

Yongzhong Huo, Yang Zhang, Yiwei Xu, Fudan Univ. (China)

Cross-linked liquid crystal polymer (LCP) is a unique multifunctional material

embodying functionality of LC in solid-state polymers. The nematic-isotropic phase transition of LC is manifested as LCP's strongly anisotropic spontaneous deformation upon thermal and/or photo actuations, namely, contraction along LC director and expansion in perpendicular plane. It is possible now to make LCP samples with predesigned spatially varying LC director fields so to produce desired shape controllability. Such ability makes LCPs very promising active materials utilizable in smart structures.

However, the mechanical behavior can be rather involved due to spatially varying anisotropic spontaneous deformation. Although finite element method could be used, analytical method is often desired to understand the mechanism and to test design principle. Considering beam shaped LCP strips with varying LC directors, we proposed a first-order shear strain beam theory to model bending due to spontaneous normal and shear strains. While it is known that thickness varying normal strain produces bending moment, we found that length varying shear strain can act as shear force to induce bending as well. Analytical examples are given to show how to design LC director fields to obtain desired bending shapes. Possible methods to obtain optimal design are discussed.

10165-43, Session 8

Multiferroic control of exchange bias: creation of small magnetic motors

John P Domann, Greg P Carman, University of California, Los Angeles (United States)

As traditional electric motors scale down, the available power density rapidly decreases. For a motor occupying a volume of 1 micron cubed, the available power density is roughly six orders of magnitude lower than a 1 millimeter cubed motor. Strain-mediated multiferroic heterostructures have recently been proposed to create high power density, micron scale, magnetic motors. These motors leverage magnetoelastic anisotropy to rotate the magnetic moment of a small disk, and use dipolar forces to couple rotors or beads to the stray magnetic field. A key challenge to the creation of these motors is to deterministically control magnetization rotations without the need for complex fabrication or control schemes. This presentation demonstrates how controlling the relative orientation of magnetic exchange bias and magnetoelastic anisotropies can be used to deterministically control motor rotations over a broad frequency range.

A Stoner-Wohlfarth magnetic macrospin model is created that couples a single domain magnetic disc to a [011] cut PMN-PT substrate. This model accounts for magnetoelastic, shape, and exchange anisotropy energies. The exchange anisotropy is rotated relative to the biaxial strain created by the PMN-PT substrate. Results demonstrate precessional magnetization dynamics deterministically controlled with an oscillating voltage on the PMN-PT substrate. This approach enables 360 degree rotations over a broad frequency range. The frequency response is provided up through ferromagnetic resonance, and power density calculations are made with comparison to existing micromechanical motors.

10165-44, Session 9

Magnetic domains evolution in NiMnGa samples loaded magento-mechanically

Constantin Ciocanel, Heidi Feigenbaum, Northern Arizona Univ. (United States)

NiMnGa is a magnetic shape memory alloy suitable for actuation, power harvesting and sensing applications. The basis for power harvesting and sensing applications is assumed to be the change in magnetic domain structured inside the material when exposed to an axial compressive stress in the presence of a bias transverse magnetic field. However, there has been no experimental validation of this theory because of the difficulties associated with visualizing magnetic domains, in general, and evolution of the magnetic domains as induced by mechanical stress, in particular. This paper presents result of the experimental investigation of magnetic domains evolution under magneto-mechanical loading and attempts to clarify the mechanisms responsible for power harvesting in MSMAs.

10165-45, Session 9

Triple-shape memory effect of styrene-based polymer

Jinsong Leng, Wenbing Li, Yanju Liu, Harbin Institute of Technology (China)

In this study, a triple-shape memory polystyrene based polymer (SMPS) is synthesized, which mainly consists of styrene, vinyl compound, and cross-linking agent (bifunctional monomer). Benzoperoxide is used as the reaction initiator, the polymerization temperature is 75 oC, and the reaction time is 24 h. Differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) results demonstrate that the crosslinked styrene based polymer possess two well-separated transition temperatures, which are subsequently used for the fixing/recovery of two temporary shapes. Furthermore, the versatile triple-shape memory functionality is demonstrated, and the result shows that the material has an excellent triple-shape memory effect. Based on the unique advantages, the SMPS material can be potentially used in sensors and actuators.

10165-46, Session 9

Programmable shape memory polycaprolactone foams and their composite actuated by microwave

Fenghua Zhang, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

As smart polymers, shape memory polymers (SMPs) are able to change shape and structure when exposed to an external stimulus, including heating, electrical and magnetic fields, water, light etc. This feature leads to potential for SMPs in many applications such as aerospace, smart textiles, robotics, automobile and biomedical engineering. SMPs can be produced to different forms and structures from nanoscale to macrolevel, including fibers, membranes, particles and foams. SMP foams have been developed due to the light weight, large deformation, etc. However, the fabrication method is too complected and the actuation speed is slow. Herein, to solve these problems, we fabricate a class of shape memory polycaprolactone foams and their composites by microwave, which can also be triggered by microwave. The merits of these foams include fast fabrication (less than 60 s), uniform pores, large compression deformation (80%) and quick shape recovery speed with in 100 s. This approach of using microwave to synthesize shape memory polymer foams in microwave oven would enable the synthesis of a wide variety of novel shape-memory foams. Moreover, microwave actuated shape memory foams can provide higher recovery speed for remote control in various applications.

10165-47, Session 9

The research of vacuum thermal cycling resistant transparent shape memory polyimide and its application in space flexible electronics

Hui Gao, Longnan Huang, Xin Lan, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Shape memory polymers and their composite materials (SMPs and SMPCs) as a kind of smart materials with the ability to memory deformed shape and recover to their original shape upon the application of an external stimulus attract more and more interests in recent years, especially their

application studies in space environments. Here in, we synthesized colorless and transparent shape memory polyimides (SMPIs) by polycondensation with bis phenol A dianhydride (BPADA) and 1,3-bis(3-aminophenoxy) benzene (BAB) and researched the effects of cycling times of vacuum thermal cycling experiments from +170 ºC to -170 ºC on their properties. Results show that SMPIs have stable properties of chemical structures, transmittance, thermo mechanical and thermal stabilities and shape memory behaviors even if 600 h vacuum thermal cycling experiments (50 cycling times). Colorless and transparent SMPIs as soften substrates for flexible electronics are not only give them shape memory functions, but also enable the structures transformation from two-dimension (2D) to three-dimension (3D), and also they can further make the application of flexible electronics in the area of space possible, such as large-area deployable space organic solar cells, large-area deployable space organic light-emitting diodes, large-area deployable space antenna, and so on.

10165-48, Session 9

Investigations on the thermo-mechanical behaviour of the CuAlNi/polyimide shape memory alloy bimorph in temperature sensing of a transformer oil

Akash K., Palani A. Iyamperumal, Chandan K., Parikshit G., Narayane Dhiraj, Reena Disawal, Bhupesh K. Lad, Vipul Singh, Indian Institute of Technology Indore (India)

Power transformer is the one of the largely important as well as one of the costly elements inthe electricity grid. Any malfunction of this element may affect the reliability of the entirenetwork and could have considerable economic impact on the system. For several reasons,overloading of power transformers beyond their rating has been reported frequently.The primary issue leading to the failure of transformer is contamination of transformer oil by the working components due to prolonged high temperature exposure. Transformer oil temperature can be utilized as a primary parameter in monitoring the life of the transformer. At present, electrical approach for monitoring transformer oil temperature such as thermocouple and thermal resistor are employed. However these techniques are vulnerable to electromagnetic interference and are limited by sensors lifetime. Other non-contact techniques are ineffective due to difficulties in processing the output signal.

In this work a CuAlNi/Polyimide shape memory alloy composite has been applied to act as a temperature sensor in mineral oils. The composite film has been developed through thermal evaporation which exhibited two-way displacement without and post-processing and training. The developed films are employed in a custom made oil rig and the suitability of using it as a circuit breaker in temperature sensing application has been probed. The circuit breaker can be triggered by measuring the displacement of the bimorph using Interferometry technique. The measurement is of non-contact type and the temperature can be monitored at regular intervals.

10165-58, Session 9

Computational simulations of contractile dielectric elastomer composites

Yali Li, Nakhiah C. Goulbourne, Univ. of Michigan (United States)

Soft electro-elastic materials are an emergent class of materials with electromechanical coupling: electric field induced actuation, strain or pressure sensing, and mechanical energy harvesting. Anisotropic electro-elastic materials consist of an isotropic matrix embedded with oriented fibers or particles that are either electro-passive or active. Here, a new soft electroactive polymer composite consisting of contractile dielectric elastomer fibers is proposed. A series of computational simulations that capture the coupled electromechanical response and account for finite deformations is conducted. The simulations explore the feasibility of enabling novel deformation modes currently unattainable by their isotropic counterparts. In previous work, we proposed a constitutive formulation for isotropic dielectric elastomers under hyperelastic conditions. The model has been shown to be robust under generalized 3D loading, finite deformations, and large electric fields. More recently, constitutive models have been developed for isotropic dielectric elastomers assuming viscoelastic behavior. In this paper, the active fiber network is treated as viscoelastic, and a new anisotropic constitutive model is proposed based on current models of physiological muscle. The model is implemented into the commercial finite element code by employing a user-defined subroutine. The FEM formulation is verified by comparing analytical solutions for uniaxial, biaxial, and simple shear tests. In the new composite, we consider the effect of spatially distributed electric fields and for the first time investigate multi-dimensional electric field activation. Distributed activation via spatially distributed fibers in a pressure-loaded membrane configured for pump-like actuation is demonstrated. We utilize our computational capability to design and optimize complex dielectric elastomer actuator composites configured for electro-hydrostatic coupling.

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10166-1, Session 1

A forty-year history of fiber optic smart structures *(Invited Paper)*

Eric Udd, Columbia Gorge Research LLC (United States)

No Abstract Available

10166-2, Session 1

Examination of single-substance multiphase material distribution in a cylindrical container using acoustic wavenumber spectroscopy

John R. Rees, Eric B. Flynn, Niall M. O'Dowd, Engineering Institute, Los Alamos National Security LLC (United States)

This paper explores the usage of a steady-state scanning laser Doppler vibrometer (LDV) system for the identification of transition areas between solid, liquid, and gaseous substances in an enclosed container. This technique images lateral surface displacement under the excitation of a single-frequency ultrasonic tone, produced by a piezoelectric actuator. Differences in measured wavenumber at discrete measurement points of a surface scan can be used to detect the boundaries between solid, liquid and gaseous regions of material. We found that the LDV system could be used to compare the relative distributions of solid wax, liquid wax, and air in a cylindrical container based on local wavenumber changes. Through the same methodology, we were able to distinguish the transition between solid and liquid epoxy in a container. Finally, by repeatedly scanning the container as a phase-changing reaction proceeded within, we established that the system can be used to monitor reactions as they progress.

10166-3, Session 1

A piezoelectric shock-loading response simulator for piezoelectric-based device developers

Jahangir S. Rastegar, Omnitek Partners, LLC (United States)

Pulsed loading of piezoelectric transducers occurs in many applications such as those in munitions firing or when a mechanical system is subjected to impact type loading. The charges generated by the impulse loading of the transducer can be used to generate electrical energy and as a sensory signal to measure the level of applied shock loading and/or to detect certain prescribed event. In such cases, the charges generated by the piezoelectric transducer are typically short lived and proper electronic circuitry has to be developed that could collect the generated charges and condition it for use by the system or device to be powered and/or for storage in an appropriate electrical energy storage device such as a rechargeable battery or a capacitor.

In many applications, such impulsive shock loading events, generally referred to as "one-shot" events, occur only once. Examples include car accident impacts or munitions explosion or gun firing or target impact. In other applications, impulsive shock loading events may occur frequently as relatively short duration pulses that are spaced regularly or randomly in time.

Design of efficient charge collection and conditioning circuits is particularly challenging in applications such as gun-fired munitions which require additional safety features to prevent accidental powering of various devices.

Currently, the collection and conditioning circuit designer can test the design either by computer modeling and simulation or by using the output of the actual piezoelectric-based device as subjected to an expected shock loading event. The computer modeling and simulation process is particularly useful to the circuit designer while developing the basic circuit design since components and design variables can be quickly changed or modified in the pursuit of more optimal circuit performance. However, due to unavoidable effects of approximations and idealizations of the component used in the circuits and the neglected effects of nonlinearities, cross-sensitivities, connecting wires and connectors, and many other factors that are either idealized or totally ignored, the simulation results are only good up to certain limits. Therefore, after computer simulation efforts have been exhausted, the circuit designer has to test the performance of the developed collection and conditioning circuit with the intended device or system to be powered. Such performance tests are necessary since they would provide realistic performance information that can then be used to vary and/or modify the design and/or its parameters and/or components to achieve optimal performance.

A need therefore exists for an electronic simulator that can be programmed to generate the electrical charges that the piezoelectric transducer of a device would generate as it is subjected to a prescribed loading generally referred to as "one-shot" events. Such piezoelectric-based device output simulators are particularly needed so that the designer of a device or system that utilizes the piezoelectric-based device as a source of electrical energy and/or as a sensor for detecting events such as shock loading can test the developed device or system under close to realistic conditions without requiring the highly costly and time consuming process of integrating it into the intended receiving system to test for its performance. The piezoelectric output simulator must obviously be capable of being programmed to provide close to realistic outputs so that the circuit designer can use the output to test the developed device or system in a close to realistic conditions.

Such a programmable piezoelectric output simulator is described in this paper. The basic circuitry of the simulator and its operation are described. Test results comparing the outputs of an actual piezoelectric element when subjected to a shock loading pulse with the simulator output are presented.

10166-4, Session 2

Piezoelectric-based hybrid reserve power sources for munitions and emergency devices

Jahangir S. Rastegar, Omnitek Partners, LLC (United States)

Reserve power sources are used extensively in munitions and other devices such as emergency devices or remote sensors that have to be powered only once and for a relatively short period of time. Reserve power sources are used in such devices due to their very long shelf life of over 20-30 years and since they can be activated when needed without any loss in their performance. Current chemical reserve power sources, including thermal batteries and liquid reserve batteries require sometimes in excess of 100-500 milliseconds to become fully activated. However, in many applications, such as in emergency devices that have to respond to certain shock loading event such as impact or in munitions that have to respond to setback acceleration event within a few milliseconds, electrical energy is required almost instantaneously following the intended event. In such applications, other power sources such as regular batteries or capacitors that have to be charged before use must be provided to power the device until the reserve battery is fully activated. In many applications such as in emergency

devices, the use of supercapacitors or primary batteries is not desirable due to their relatively short shelf life and loss of power over time and in some applications due to environmental factors such as low or high temperatures. In most munitions the use of primary batteries is impractical due to safety as well as shelf life considerations.

The amount of electrical energy that is required by most emergency equipment as well as munitions electronics before chemical reserve batteries are fully activated is generally small and can be provided by properly designed piezoelectric-based energy harvesting devices. In this paper the development of a hybrid reserve power source is being reported that is obtained by the integration of a piezoelectric-based energy harvesting device with a thermal or liquid reserve battery that can provide power almost instantaneously upon the detection of munitions firing or other similar events in other applications.

This article provides a review of the state of the art in piezoelectric-based electrical energy harvesting methods and devices and their charge collection electronics for use in the developed hybrid power sources. The design of such a hybrid piezoelectric and reserve battery based power source is described in detail. Computer modeling of the power source and simulation of its operation once subjected to activation event is provided. The testing platform developed for testing the piezoelectric component of the power source and its electronic safety and charge collection electronics is described and test results are provided and discussed in detail.

10166-5, Session 2

Modal analysis of a loaded tire using non-contact measurements and piezoelectric excitation

Ipar Ferhat, Pablo A. Tarazaga, Virginia Polytechnic Institute and State Univ. (United States)

Highly complex nature of tires requires very precise test data to model the structure accurately. Highly damped characteristics, geometric features and operational conditions of tires cause various testing difficulties that affects the reliability of the modal testing. One of the biggest challenges of tire testing is exciting the whole region of the tire at once. Conventionally, impact hammers, shakers, and cleats are used as an excitation input. The shortcomings of these excitation methods are the directional and force inconsistency of hammer impacts, coupled dynamics of shakers and speed limitations of cleat excitation. Other challenges of modal testing for tires are the effect of added mass due to sensor attachments and difficulty of vibration measurement of a rotating tire with accelerometers. In order to remedy these problems, we conduct experimental modal analysis (EMA) using a non-contact measurement technique and piezoelectric excitation. For non-contact measurement, a 3-D scanning laser doppler vibrometer (SLDV) is used. For the piezoelectric excitation, Micro Fiber Composite (MFC) patches are used due to their flexible nature and power capacity. This excitation method can also be crucial to excite rotating tires since the cleat excitation is not adequate for low-speed measurements. Furthermore, the piezoelectric actuation system can be used as sensors as well as noise controllers in operating conditions. For this work, we run experiments for the tire and wheel separately, tire-wheel assembled in free-free conditions, and the tire-wheel system under loaded conditions to characterize each component separately and as a coupled system. Experiments are carried out for the frequency bandwidth up to 500Hz to capture the structural behavior under high-frequency excitations and its coupled behavior to airborne vibrations.

10166-6, Session 2

Wearable Spiral Passive Electromagnetic Sensor (SPES) glove for sign language recognition

Onorio Iervolino, Michele Meo, Univ. of Bath (United Kingdom)

The sign language is a method of communication for deaf-mute with articulated gestures and postures of hands and fingers to represent alphabet letter or complete words. Recognising gestures is a difficult task, due to intrapersonal and interpersonal variations in performing them. This paper investigates the use of Spiral Passive Electromagnetic Sensor (SPES) as a motion recognition tool. An instrumented glove integrated with wearable multi-SPES sensors was developed to encode data and provide a unique response for each hand gesture. The device can be used for recognition of gestures; motion control and well-defined gesture sets such as sign languages. Each specific gesture was associated to a unique sensor response. The gloves encode data regarding the gesture directly in the frequency spectrum response of the SPES. The absence of chip or complex electronic circuit make the gloves light and comfortable to wear. Results showed encouraging data to use SPES in wearable applications.

10166-7, Session 2

A new class of monolithic seismometers and accelerometers for commercial and industrial application: the UNISA folded pendulum

Fabrizio Barone, Gerardo Giordano, Univ. degli Studi di Salerno (Italy)

In the last decade the request of mechanical seismometers (and accelerometers) in different fields of research is largely increased such as the number of applications, with requirements more and more stringent: large measurement bands (10 uHz ÷1 kHz), very high sensitivities (down to 10 pm/sqrt(Hz), high directivities (> 10000), compactness (< 10 cm side), lightness (< 1.0 kg), high thermal stability very often coupled with ultra-high vacuum (< 10 nTorr) and/or cryogenics compatibility. Commercial mechanical seismometers and accelerometers, based on the mechanical architectures of classical oscillators (simple pendulum, inverted pendulum, spring-mass oscillator), although optimized with the introduction of effective control and signal readout techniques, can satisfy only subsets of the above requirements.

In this paper we present a new class of sensors, that, based on an innovative design and implementation of the classical mechanical architecture known as Watt's linkage (4-bar linkage), appears to be one of the most promising architectures for the design of mechanical seismometers and accelerometers (horizontal, vertical and angular). In fact, the Watt's linkage can be configured in such a way to reproduce a combination of a simple pendulum and of an inverted pendulum both connected to one end by means of joints to a bar (the central mass or inertial mass) and to the other ends by means of other joints to a supporting structure fixed to the ground (frame).

In particular, we present and discuss the characteristics and monolithic implementations of tunable uniaxial and triaxial mechanical seismometers and accelerometers (horizontal, vertical and angular) based on the UNISA Folded Pendulum innovative configuration, protected by three international patents and commercially available, whose main physical and mechanical characteristics can be synthesized in scalability, frequency tuning; measurement band 10^(-7) ÷ 100 Hz; linear sensitivity ~ 10^(-14) m/√Hz or angular sensitivity ~10^-10 rad/√Hz, directivity >10^4, weight < 250 g, dimensions <10 cm) coupled to a large insensitivity to environmental noises, compactness, and capability of operating in ultra high vacuum (UHV) and cryogenic environments.

Typical applications of this class of monolithic sensors are in the field of earthquake engineering, seismology, geophysics, civil engineering (buildings, bridges, dams, etc.), space (satellite and space-crafts inertial guide), and, in general, in all the applications requiring large band-low frequency performances coupled with high sensitivities. Some selected applications and the comparison with commercial sensors are also presented in the paper.

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10166-8, Session 2

The development of two broadband vibration energy harvesters with adaptive conversion electronics

Dan J. Clingman, Boeing Research and Technology (United States)

Historically, piezoelectric vibration energy harvesters have been limited to operation at a single structurally resonate frequency. A piezoceramic energy harvester such as a bimorph beam operating at structural resonance exchanges energy between dynamic and stain regimes which increases the coupling between piezoceramic deformation and electrical charge generation. Two BVEH mechanisms are presented which exploit strain energy management to reduce inertial forces needed to deform the piezoceramic thus increasing the coupling between structural and electrical energy conversion over broadband vibration spectrum.

Broadband vibration excitation produces a non-sinusoidal wave form from the BVEH device. An adaptive energy conversion circuit was developed that exploits a buck converter to capture the complex wave form energy.

10166-9, Session 3

Piezoelectric-based actuators for improved tractor-trailer performance *(Invited Paper)*

David Menicovich, Actasys (United States); Michael Amitay, Rensselaer Polytechnic Institute (United States) and Actasys (United States); Daniele Gallardo, Actasys (United States)

The application of piezo-electrically-driven synthetic-jet-based active flow control to reduce drag on tractor-trailers and to improve thermal mixing in refrigerated trailers was explored on full-scale tests. The active flow control technique that is being used relies on a modular system comprised of distributed, small, highly efficient actuators. These actuators, called synthetic jets, are jets that are synthesized at the edge of an orifice by a periodic motion of a piezoelectric diaphragm(s) mounted on one (or more) walls of a sealed cavity. The synthetic jet is zero net mass flux (ZNMF), but it allows momentum transfer to flow. It is typically driven near diaphragm and/or cavity resonance, and therefore, small electric input [O(10W)] is required. Another advantage of this actuator is that no plumbing is required. The system doesn't require changes to the body of the truck, can be easily reconfigured to various types of vehicles, and consumes small amounts of electrical power from the existing electrical system of the truck. The actuators are operated in a closed feedback loop based on inputs received from the tractor's electronic control unit, various system components and environmental sensors. The data are collected and processed on-board and transmitted to a cloud-based data management platform for further big data analytics and diagnostics. The system functions as a smart connected product through the interchange of data between the physical truck-mounted system and its cloud platform.

10166-10, Session 3

Modeling and optimization of piezoelectric bimorph-driven synthetic jet actuators using structural-acoustic FEM

Tianliang Yu, George A. Lesieutre, Pennsylvania State University (United States); Steven F. Griffin, Daniel P. Brzozowski, Aaron M. Sassoon, The Boeing Company (United States)

Synthetic jet actuators are of intense interest for potential applications to active flow control and thermal management. Resonant piezoelectric-diaphragm-type configurations are commonly considered. Modeling of such actuators remains a challenge due to complexities associated with both electro-elastic and fluid-structure coupling, as well as potential non-linearities in both. A key metric for synthetic jet performance is the time-averaged jet momentum. Linear lumped-element modeling is an approach that has been used to consider the performance of such coupled systems, and it has demonstrated the ability to predict jet momentum in terms of input frequency and voltage. However, it lacks accuracy for high-amplitude response, as it neglects nonlinearity and increasing losses. In this paper, multi-physics finite element models are used to simulate device performance. Acoustics theory was used to simplify the fluid dynamics model, and circular PZT-5A plates in a bimorph configuration were used to drive a cylindrical fluid cavity near a coupled structural-acoustic resonance. A nonlinear impedance boundary condition was devised to model the acoustic resistance of the exterior space. The fluid acoustics equations and piezo-structural equations were coupled and solved simultaneously in the frequency domain using COMSOL. RMS jet momentum was determined as a function of driving frequency and voltage. When the input frequency matches the first coupled structural-acoustic resonance frequency, the jet momentum is a maximum; however, the output jet momentum increases at a less-than-linear rate with input voltage. Continuing research addresses optimization of the device configuration to best exploit various piezoelectric materials; the final paper will include these results.

10166-11, Session 3

A self-tuning tuned mass damper

Steven F. Griffin, The Boeing Co. (United States)

Tuned mass dampers (TMDs) are heavily damped resonant devices which add damping to lightly damped vibrational modes of a structure by dynamically coupling into the lightly damped modes. In practice, a TMD is a damped spring/mass resonator that is tuned so that its frequency is close to a lightly damped mode on the host structure. The TMD is attached to the host structure at a location of large amplitude motion for the mode in question and its motion is coupled into the host structure's motion. If the TMD is tuned correctly, two damped vibrational modes result, which take the place of the original lightly damped mode of the host structure and heavily damped mode of the TMD. Since aerospace structures tend to respond unfavorably at lightly damped modes in the presence of a dynamic

disturbance environment, introduction of one or several TMDs can greatly reduce the dynamic response of a structure by damping problematic modes. A self-tuning tuned mass damper is described that can perform all the steps necessary to automatically tune itself and minimize the response of a structure with lightly damped modes and a dynamic excitation. The self-tuning TMD concept introduced here uses a voice coil / magnet combination as

-an actuator which enables an innovative stiffness adjustment mechanism

-a loss mechanism for the tuned mass damper

-a means of excitation for identifying lightly damped modes of the host structure

Along with an accelerometer and a tethered power supply/ computer, the self-tuning TMD can automatically identify and damp lightly damped modes.

10166-12, Session 3

A three-dimensional vibration exciter for engineering testing

Mohammadsadegh Saadatzi, Sourav Banerjee, Univ. of South Carolina (United States)

Researchers use exciters in mechanical and industrial laboratories to provide the required vibrations which can be found in most common ambient sources of vibrations like motors, pumps, ducts and pipes. The primary duty of a vibration exciter is to excite a physical model using generated signals as the input of exciters for the purpose of simulating a real vibrating condition parameters. This article presents a 3-Dimensional (3-D) mechanical vibrations exciter. A novel 3-D excitation generator means of mechanical and electrical characteristics of electrodynamics and acoustic concepts and using shakers and speakers is proposed here and aimed to improve the working frequency. Needs for a 3-D vibration exciter, the structure idea of working device and its important assemblies are described vividly. Vibration frequency of each exciter in the device (shakers and speakers) from 50Hz to 1.5kHz are designed to be controlled individually using a control circuit, which is one of the most challenging part of this work. Also, using MATLAB, a Graphical user interface is developed to manage the input variables (e.g. excitation frequency). This proposed exciter can be utilized in different research fields like fatigue testing of specimens or educational demonstration and study of dynamic properties of structures in vibration testing, structural response testing and resonance searching. In this paper, for the purpose of proposed machine validating, the proposed device is used as a test bench to test a cantilever energy harvester which is placed in a 3-D shape on the end effector of the exciter. At the end, comparison of experimental results is used to validated the functionality of device.

10166-13, Session 4

Preliminary aeroelastic assessment of a large aeroplane equipped with a camber-morphing aileron

Rosario Pecora, Francesco Amoroso, Maurizio Arena, Rita Palumbo, Univ. degli Studi di Napoli Federico II (Italy); Gianluca Amendola, Ignazio Dimino, Ctr. Italiano Ricerche Aerospaziali (Italy)

The development of adaptive morphing wings has been individuated as one of the crucial topics in the greening of the next generation air transport. Research programs have been lunched and are still running worldwide to exploit the potentials of morphing concepts in the optimization of aircraft efficiency and in the consequent reduction of fuel burn. In the framework of CRIAQ MDO 505, a joint Canadian and Italian research project, an innovative camber morphing architecture was proposed for the aileron of a reference civil transportation aircraft; aileron shape adaptation was conceived to increase roll control effectiveness as well as to maximize overall wing efficiency along a typical flight mission. Implemented structural solutions and embedded systems were duly validated from through ground tests carried out on a true scale prototype.

Relying upon the experimental modes of the device in free-free conditions, a rational analysis was carried out in order to investigate the impacts of the morphing aileron on the aeroelastic stability of the reference aircraft. Flutter analyses were performed in compliance with EASA CS-25 airworthiness requirements and referring -at first- to nominal aileron functioning. In this way, safety ranges for aileron control harmonics and degree of mass-balance were defined to avoid instabilities within the flight envelope. Trade-off analyses were finally addressed to justify the robustness of the adopted massbalancing as well as the persistence of the flutter clearance in case of relevant failures of the morphing system components.

10166-14, Session 4

Touchscreen surface based on interaction of ultrasonic guided waves with a contact impedance

Nicolas Quaegebeur, Patrice Masson, Nicolas Beaudet, Philippe Sarret, Univ. de Sherbrooke (Canada)

In the present paper, a touchscreen device is proposed, based on guided wave reflection and transmission induced by the presence of an object. The principle uses the advantages of other acoustic waves devices in terms of simplicity and applicability to any thin surface but is not subject to classical drawbacks (single-touch, sensitivity to scratches or contaminant, impossibility to follow motion of contact point). The theoretical interaction of guided waves with a contact impedance are first derived in order to define the requirements of the sensor in terms of frequency range, mode, sensor type and location, and embedded electronics. Design criteria and experimental validation on a small prototype (200 x 250 mm) are proposed to demonstrate the potential of the approach for simple, robust and reliable contact detection of point-like or extended objects for consumer electronics or biomedical applications.

10166-15, Session 4

The impact of magnetorheological semi-active stabilizer bar on automobile rollover

Xian-Xu Bai, Shi-Xu Xu, Hefei Univ. of Technology (China)

Magnetorheological (MR) fluids are a smart material with properties of rapid-response and large controllable range. MR actuators using MR fluids have been widely developed. Aim at improving the safety (anti-roll performance) and ride comfort of automobiles during fast cornering or over road irregularities, a semi-active stabilizer bar employing a rotary MR damper is proposed in this paper. The proposed stabilizer bar is used to provide small torsional rigidity at low speed to improve ride comfort, while large torsional rigidity to enhance the safety at high speed cornering. To verify the feasibility and effectiveness of the proposed semi-active stabilizer bar, the mathematical model of the semi-active stabilizer bar is established, and the passive-on state dynamic performance of a specific vehicle suspension system is studied via software ADAMS. The influence of semi-active stabilizer bar on automobile rollover is investigated based on the co-simulation of ADAMS and MATLAB/Simulink, and the performance is compared and analyzed with the conventional stabilizer bar. The results show that: (1) the automobile equipped the MR semi-active stabilizer bar requires smaller roll angle than the conventional one when at high speed cornering, i.e., better safety; (2) when low speed cornering, the automobile requires larger roll angle, i.e., better ride comfort; and (3) both the critical lateral acceleration of automobile rollover and anti-roll performance are enhanced.

10166-16, Session 5

Challenges and state of the technology for printed sensor array for structural monitoring

Shiv Joshi, NextGen Aeronautics Inc (United States); Scott Bland, Robert DeMott, NextGen Aeronautics, Inc. (United States); Nickolas Anderson, Gregory Jursich, Univ. of Illinois at Chicago (United States)

Printed sensor arrays are attractive for reliable, low-cost, and large-area mapping of structural systems. These sensor arrays can be printed on flexible substrates or directly on monitored structural parts. This technology is sought for continuous or on-demand real-time diagnosis and prognosis of complex structural components. In the past decade, many innovative technologies and functional materials have been explored to develop printed electronics and sensors. For example, an all-printed strain sensor array is a recent example of a low-cost, flexible and light-weight system that provides a reliable method for monitoring the state of aircraft structural parts. Among all-printing techniques, screen and inkjet printing methods are well suited for smaller-scale prototyping and have drawn much interest due to maturity of printing procedures and availability of compatible inks and substrates. Screen printing relies on a mask (screen) to transfer a pattern onto a substrate. Screen printing is widely used because of the high printing speed, large selection of ink/substrate materials, and capability of making complex multilayer devices. The complexity of collecting signals from a large number of sensors over a large area necessitates signal multiplexing electronics that need to be printed on flexible substrate or structure. As a result, these components are subjected to same deformation, temperature and other parameters for which sensor arrays are designed. The characteristics of these electronic components, such as transistors, are affected by deformation and other environmental parameters which can lead to erroneous sensed parameters. The manufacturing and functional challenges of the technology of printed sensor array systems for structural state monitoring are the focus of this presentation. Specific examples of strain sensor arrays will be presented to highlight the technical challenges.

10166-17, Session 5

Reinforcing cementitious structures by pH activated in-situ shrinking microfiber

Sundong Kim, Patrick C. Lee, Dryver R. Huston, Ting Tan, The Univ. of Vermont (United States)

The study describes the development of active post-cure shrinking fiber reinforcement strengthening technology for concrete structures. Fiber reinforcing is a commonly used technology in industry due to its cost, and ability to be easily applied into a variety of shapes of structures. Unlike incumbent passive reinforcing technology, microfibers made of pH-sensitive polymers, which shrink under the high pH conditions of fresh Portland cement concrete, activate and induce pre-stressing or post-tensioning by responding to the variation in pH. Tests show that the pH of a concrete mixture increases up to 12, and the shrinking fibers would be activated as the concrete cures. Chitosan, a natural pH-sensitive polymer that reacts to high pH environment has been reviewed for the base material of shrinking microfiber. However, preliminary results show that the microfiber made of pure chitosan has low tensile strength for reinforcing (46.2 MPa). Polyethylene (PE) or/and Polyethylene Oxide (PEO) is blended with chitosan to strengthen the tensile properties. Chitosan/PE, chitosan/PEO or chitosan/PE-PEO microfibers have potential to create more sturdy structures that tend not to crack in tension, compression, and distortional loads. If successful, it would be possible to create a whole new class of high-performance fiber reinforced composites.

10166-18, Session 5

A portable integrated system to control the active needle

Minji Jo, Univ. of Hawai'i at Manoa (United States); Hashem Ashrafiuon, Villanova Univ. (United States); Bardia Konh, Univ. of Hawai'i at Manoa (United States)

Needle insertion is a frequently used technique in several percutaneous procedures such as brachytherapy, breast biopsy, and thermal ablation. Recently, shape memory alloy wires have been suggested for activating surgical needles. Using the robust actuation capabilities of the SMA wires, the accuracy of such medical procedures is sought to be drastically improved.

This work introduces a portable integrated system to run and control the active needle device. There are several devices that have to work simultaneously in order to perform a reliable successful task. A Raspberry PI (RPI) was selected to be the central tool commanding the linear stage motor that guides the needle into the tissue, and the power supply unit that provides the appropriate current for SMA actuators. The needle tip movement was captured using an electromagnetic tracking system.

Python program was used to communicate between the RPI and the other integrated devices. The programming algorithm and its details have been explained in this work. A simple feedback control algorithm was also included in the code in order to obtain a smooth movement of the needle tip. The input parameters were the amount of current and the speed of the linear stage, while the feedback parameter was selected to be the needle tip movement. The light weight of this controlling device with all the components combined would make it very convenient to bring it to the surgeons who have to be trained to use this new active needle product.

10166-19, Session 5

Auto-Gopher-II: an autonomous wireline rotary-hammer ultrasonic drill

Mircea Badescu, Stewart Sherrit, Hyeong Jae Lee, Xiaoqi Bao, Yoseph Bar-Cohen, Shannon P. Jackson, Jet Propulsion Lab. (United States); Kris Zacny, Gale L. Paulsen, Honeybee Robotics (United States)

Developing technologies that would enable in future NASA exploration missions to penetrate deeper into the subsurface of planetary bodies for sample collection is of great importance. Performing these tasks while using minimal mass systems and with low energy consumption is another set of requirements imposed on such technologies. A deep drill, called Auto-Gopher II, is currently being developed as a joint effort of the JPL's NDEAA laboratory and Honeybee Robotics Corp. The Auto-Gopher II is a wireline rotary-hammer drill that combines formation breaking by hammering using an ultrasonic actuator and cuttings removal by rotating a fluted bit. The hammering mechanism is based on the Ultrasonic/Sonic Drill/Corer (USDC) that has been developed as an adaptable tool for many drilling and coring applications. The USDC uses an intermediate free-flying mass to transform high frequency vibrations of a piezoelectric transducer horn tip into sonic hammering of the drill bit. The USDC concept was used in a previous task to develop an Ultrasonic/Sonic Ice Gopher and then integrated into a rotary hammer device to develop the Auto-Gopher-I. The lessons learned from these developments are being integrated into the development of the Auto-Gopher-II, an autonomous deep wireline drill with integrated cuttings and sample management and drive electronics. Subsystems of the wireline drill are being developed in parallel at JPL and Honeybee Robotics Corp. This paper will present the development efforts of the piezoelectric actuator, cuttings removal and retention flutes and drive electronics

10166-20, Session 5

Experimental validation of a true-scale morphing flap for large civil aircraft applications

Rosario Pecora, Francesco Amoroso, Maurizio Arena, Maria Chiara Noviello, Francesco Rea, Univ. degli Studi di Napoli Federico II (Italy)

Within the framework of the JTI-Clean Sky (CS) project, and during the first phase of the Low Noise Configuration Domain of the GRA-ITD, the preliminary design and technological demonstration of a novel wing flap architecture were addressed. Research activities were carried out to substantiate the feasibility of morphing concepts enabling flap camber variation in compliance with the demanding safety requirements applicable to the next generation green regional aircraft, 130-seats with open rotor configuration.

The driving motivation for the investigation of such a technology was found in the opportunity to replace a conventional double slotted flap with a single slotted camber-morphing flap assuring similar high lift performances -in terms of maximum attainable lift coefficient and stall angle- while lowering emitted noise and system complexity. Studies and tests were limited to a portion of the flap element obtained by slicing the actual flap geometry with two cutting planes distant 0.8 meters along the wing span.

Further activities were then addressed in order to increase the TRL of the validated architecture within the second phase of the CS-GRA. Relying upon the already assessed concept, an innovative and more advanced flap device was designed in order to enable two different morphing modes on the basis of the A/C flight condition / flap setting:

Mode1, Overall camber morphing to enhance high-lift performances during take-off and landing (flap deployed);

Mode2, Tab-like morphing mode. Upwards and downwards deflection of the flap tip during cruise (flap stowed) for load control at high speed.

A true-scale segment of the outer wing flap (4 meters span with a mean chord of 0.9 meters) was selected as investigation domain for the new architecture in order to duly face the challenges posed by real wing installation.

Advanced and innovative solutions for the adaptive structure, actuation and control systems were duly analyzed and experimentally validated through static and dynamic ground tests thus proving the overall device compliance with industrial standards and applicable airworthiness requirements.

10166-21, Session PMon

Reversible creation of smart nanostructures for commercial approaches

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 1:20 on lines with widths from 50-500 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.

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10167-1, Session 1

Can artificial intelligence (AI) provoke the revolutionary change in the medical field? *(Keynote Presentation)*

Uhn Lee, Gachon Univ. (Korea, Republic of)

Artificial Intelligence is changing the medical profession in many ways.

Recently IBM Watson for Oncology has been applied to the treatment site. This is just the beginning.

In the near future, Artificial Intelligence would be spread to all other areas, including cardiovascular disease, diabetes, intractable neurologic disease etc.

Artificial Intelligence must provoke the numerous changes in medical field. AI will result in a revolutionary change in all medical practice system as well as the diagnostic or therapeutic support

The first change we can expect, is the democratization of medical field. In fact, the healthcare system does not provide the fair access right for everyone. The quality of care being provided significantly different in accordance with the difference of income or social status. But realistically providing the best care equitably to all people is almost impossible. But if we use the AI trained by world-class medical experts, it can reduce these inequality.

The second change is, AI can reduce the medical expenses without sacrificing the quality of care. Exponentially increasing medical costs is already difficult to tolerable. One of the major causes of increased health care is a hospital rendering of the patient. The reason for this hospital rendering is the distrust of the patient to the decision-making process of doctors. AI can significantly reduce this hospital rendering. When patients visit the hospital's first, patients will be able to get the best precise through the AI based care. The patient is able to save time, as well as medical expenses. This leads to the entire national healthcare cost savings.

The third change is the creation of business opportunities that accompany the changes in medical practice. AI will provide many new business opportunities in cooperate with Precision Medicine, Big Data, Telemedicine, Sensing Devices, Wearable Computer and Drones.

Consequently, AI is leading to many changes but at the same time the medical profession will be given a new chance.

After all AI must be the enhancer of medical doctor's ability, not Job terminator system

10167-2, Session 1

Wearable nanosensor systems and their applications in healthcare

Mouli Ramasamy, Prashanth Kumar, Pennsylvania State Univ. (United States); Vijay K. Varadan, Pennsylvania State Univ (United States)

The development of intelligent miniaturized nano-bio-and info-tech based sensors capable of wireless communication will fundamentally change the way we monitor and treat patients with chronic disease and after surgery. These new sensors will allow the monitoring of the patients as they maintain their normal daily activities, and provide warning to healthcare workers when critical events arise. This will facilitate early discharge of patients from hospitals as well as providing reassurance to patients and family that potential problems will be detected at an early stage. The use of continuous monitoring allows both transient and progressive abnormalities to be reliably detected thus avoiding the problems of conventional diagnosis and monitoring methods where by data is captured only for a brief period during hospital/clinic visits. We have been working with a printable organic semiconductor and thin film transistor, and have fabricated and tested various biosensors that can measure important physiological signs before and after surgery. Integrated into "smart" fabrics - garments with wireless technology – and independent e-bandaid sensors, nanosensors in tattoos and socks, minimally invasive implantable devices, the sensor systems will be able to monitor a patient's condition in real time and thus provide point-of-care diagnostics to health-care professionals and greater freedom for patients. Selected videos of patients will be shown in the talk.

10167-3, Session 1

Carbon nanoparticle doped micro-patternable nano-composites for wearable sensing applications

Ajit Khosla, Yamagata Univ. (Japan)

This talk focuses on preparation, characterization and micropatterning of electrically conducting KETJENBLACK carbon black nanoparticle (80 nm-diameter) doped Polydimethylsiloxane (PDMS) by employing extrusion mixing. Previously, we had reported fabrication of various micropatternable nanocomposites for wearable sensing applications vis solvent assisted ultrasonic mixing technique[1-16] . Extrusion mixing has an advantage as no organic solvents are used and homogenous dispersion of carbon nanoparticles is observed, which is confirmed by SEM analysis. The developed nanocomposite can be micropatterened using standard microfabrication techniques. It is also observed that percolation threshold occurs at 0.51 wt% of carbon nanoparticles in polymer matrix. Examples of developed nano-composites for wearable sensing applications for precision medicine will also be discussed.

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10167-4, Session 1

Left lateral decubitus position on patients with atrial fibrillation and congestive heart failure

Vijay K. Varadan, Prashanth Kumar, The Pennsylvania State Univ. (United States)

Novel wireless nanosensor systems will be presented on the effect of left lateral decubitus positon while sleeping on Atrial Fibrillation (AFib) and Congestive Heart Failure (CHF). The patient test data provide the following findings, a) the patients tend to avoid lying on their left side (left lateral decubitus, LLD, position), b) it was found that this is due to the development of dyspnea in the LLD position, termed ‘trepopnea, which is associated with the elevation of pulmonary venous pressures resulting in pulmonary edema and c) the LLD position is associated with higher sympathetic nervous activity in patients with CHF

10167-5, Session 1

Ventricular arrhythmia and sudden cardiac death: catheter based sensor and mapping system of heart

Vijay K. Varadan, The Pennsylvania State Univ. (United States); Prashanth Kumar, Mouli Ramasamy, Pennsylvania State Univ. (United States)

Ventricular arrhythmias in the heart and the rapid heartbeat of ventricular tachycardia can lead to sudden cardiac death. This is a major health issue worldwide. What is needed is to develop a catheter based sensor and mapping approach which will provide the mechanisms of ventricular arrhythmia, and effectively prevent and treat the same, potentially save life.

10167-6, Session 2

3D printing of soft-matter to open a new era of soft-matter MEMS/robotics *(Keynote Presentation)*

Hidemitsu Furukawa, Yamagata Univ. (Japan)

3D printing technology is becoming useful and applicable by the progress of information and communication technology (ICT). It means 3D printer is a kind of useful robot for additive manufacturing and is controlled by computer with human-friendly software. Once user starts to use 3D printing of soft-matter, one can immediately understand computer-aided design (CAD) and engineering (CAE) technology will be more important and applicable for soft-matter systems. User can easily design soft-matter objects and 3D-print them. User can easily apply 3D-printed soft-matter objects to develop new research and application on MEMS and robotics. Here we introduce the recent progress of 3D printing (i.e. additive manufacturing), especially focusing on our 3D gel printing. We are trying to develop new advanced research and applications of 3D gel printer, including GEL-MECHANICS, GEL-PHOTONICS, and GEL-ROBOTICS. In the gel-mechanics, we are developing new gel materials for mechanical engineering. Some gels have high-mechanical strength and shape memory properties. In the gel-photonics. We are applying our original characterizing system, named ‘Scanning Microscopic Light Scattering (SMILS)’, to analyze 3D printed gel materials. In the gel-robotics, we focus on 3D printing of soft parts for soft-robotics made form gel materials, like gel finger. Also we are challenging to apply 3D gel printing to start new company, to innovate new businesses in county side, and to create new 3D-printed foods.

10167-7, Session 3

Scalable metal additive manufacturing using optically addressable beam shaping elements

Manyalibo J. Matthews, Gabriel M. Guss, Derrek R. Drachenberg, Chrstopher M. Spadaccini, Lawrence Livermore National Lab. (United States)

Selective Laser Melting (SLM) of metal powder bed layers, whereby 3D metal objects can be printed from a digital file with unprecedented design flexibility, is spurring manufacturing innovations from medical to heavy industry. Because the SLM is based on raster-scanning a laser beam over each layer, the process is slow (hrs to days), thus limiting wider spread use of SLM. Here we demonstrate the use of a photolithographic method for 3D metal printing, using an optically-addressable light valve (OALV) as the photomask, to print entire layers of metal powder at once. An optical sheet of multiplexed ~5kW, 20 ms diode and ~1 MW, 7 ns Q-switched laser pulses are used to selectively melt each layer. The patterning of NIR light is accomplished by imaging 470 nm light onto the transmissive OALV, which consists of polarization-selective nematic liquid crystal sandwiched between a photoconductor and transparent conductor for switching. Complete builds of metal parts using this technique are demonstrated and the scaling behavior up to 1 m3 builds is analyzed. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

10167-8, Session 3

3D printing of wearable fractal based sensor systems for neurocardiology and healthcare

Vijay K. Varadan, Mouli Ramasamy, The Pennsylvania State Univ. (United States)

Neurocardiology is the pathophysiological interplay of nervous and cardiovascular systems. The communication between the heart and brain has revealed various methodologies in healthcare that could be investigated to study the heart-brain interactions and other cardiovascular and neurological diseases. A textile based wearable nanosensor system in the form of e-bra, e-shirt, e-headband, e-brief, underwear etc, was presented in this SPIE conferences earlier for noninvasive recording of EEG and EKG, and showing the correlation between the brain and heart signals. In this paper, the technology is expanded further using fractal based geometries using 3D printing system for low cost and flexible wearable sensor system for healthcare.

10167-9, Session 3

3D printing and IoT for personalized everyday objects in nursing and healthcare

Yoshihiro Asano, Hiroya Tanaka, Shoko Miyagawa, Junki Yoshioka, Keio Univ. (Japan)

Today, application of 3D printing technology for medical use is getting popular. It strongly helps to make complicated shape of body parts with functional materials. We can complement injured, weakened or lacked parts, and recover original shape and functions.

However, these cases are mainly focusing on the symptom itself, not on everyday lives of patients. With life span extending, many of us will live a life with chronic disease for long time. Then, we should think about our living environment more carefully. For example, we can make personalized everyday objects and support their body and mind.

Therefore, we use 3D printing for making everyday objects from nursing / healthcare perspective. In this project, we have 2 main research questions.

The first one is how to make objects which patients really require. We invited many kinds of people such as engineer, nurses and patients to our research activity. Nurses can find patient's real demands firstly, and engineers support them with rapid prototyping. Finally we found the best collaboration methodologies among nurses, engineers and patients.

The second question is how to trace and evaluate usages of created objects. Apparently, it's difficult to monitor user's activity for a long time. So we're developing the IoT sensing system, which monitor activities remotely. We enclose a data logger which can lasts about one month with 3D printed objects. After one month, we can pick up the data from objects and understand how it has been used.

10167-10, Session 3

Development of low-cost open source 3D gel printer "RepRap SWIM-ER"

Kei Sato, Ajit Khosla, Azusa Saito, Samiul Basher, Takafumi Ota, Taishi Tase, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels are the soft Polymer material having the network structure such as a jungle gym that can include a large quantity of solvents. They are expected that used as the Medical supplies and the industrial materials. However, the molding of complicated shape of the gel is difficult. To solve this problem, 3D gel printer "SWIM-ER" was developed in the Furukawa laboratory. 3D molding of the gel is enabled by this device. However, all companies and research organizations do not have such a device. Therefore, we use "RepRap" that is the 3D printer produced with open source hardware. Because "RepRap" is the open source, improvement and sale are possible freely. Our purpose is to develop SWIM-ER from RepRap, and to deliver it as low-cost open source 3D gel printer "RepRap SWIM-ER".

10167-11, Session 4

Depth of field extended imaging method based on intensification of time and spatial expansion

Lihui Wang, Tomohiko Hayakawa, Masatoshi Ishikawa, The Univ. of Tokyo (Japan)

Microscopy imaging optics can capture high resolution image at a certain focus plane, but the information outside that focal plane will become blur and the information will be lost. If we adjust the optics stop of the optics system, the depth of field can be extended, but the resolution will be reduced; on the other hand, if we manually adjust the focal length, we can get the information on another focusing planes, however the manually adjustment is too slow to observe a high speed moving target in vivo.

The speed of light varies when light travels in different materials. When a transparent plate was placed in front of a camera, the focusing point of the original system would be shifted, due to the decreasing of the transmission speed.

We proposed a variable focus system for extending the depth of field of the microscopy imaging system. Dozen different thickness transparent plates were clock-like circularly mosaicked on a round disk, and the disk was placed behind the last lens of the original optics system. The disk was rotated by a motor. The capture motion was occurred when the axis of the main optics and the center of every transparent plates were coincidence. By doing this, there would be twelve frames which saved different image information of different focal length planes. In our experiment, a depth of field target was placed as the observe target and twelve frames were captured. We also confirmed that the focal length plane was gradually shift in these frames. The part of every frame which in focusing can be abstracted and merged into an all-depth-focused frame.

10167-12, Session 4

Conductive polymer sensor arrays for smart orthopaedic implants

Carolina Micolini, Frederick B. Holness, Western Univ. (Canada); James A. Johnson, Lawson Health Research Institute (Canada); Aaron D. Price, Western Univ. (Canada)

Total reverse shoulder arthroplasty (RSTA) is a relatively new orthopedic procedure that has shown promising short-term results for the treatment of glenohumeral arthritis and massive rotator cuff tears. RTSA is limited in that the implant's functional lifespan is governed by wear resistance, which is itself determined by notching and the joint reaction force of the UHMWPE component and the body's response to the resulting debris. Previous efforts to measure contact points have been mainly confined to strain gauges monitoring contact loads at a discrete point of the implant's surface. Furthermore, most biomechanical studies of the reversed implant do not accurately mimic an appropriate clinical environment; hence accurate force measurement is not possible. This project aims to elucidate stress distributions within joint implant components by means of embedded conjugated polymer sensors, with the ultimate goal of eliminating revision surgeries through enhanced wear performance and fixation stability.

Herein we employ specially developed additive manufacturing processes enabling the direct ink writing of conductive polyaniline structures in conjunction with a modified 3D printer to deposit structural and sensing materials concurrently. Through the application of these fabrication

techniques and the piezoresistive properties of polyaniline, we have established the capability to manufacture implant components embedded with smart-polymer sensors. These methods have been applied to RSTA implant designs to produce a smart humeral cup. This device provides insight into mechanical stress distributions within the humeral cup to identify and mitigate the most critical potential failure sites.

10167-13, Session 5

Detection of complex molecular samples by low-cost surface enhanced raman spectroscopy (SERS) substrate

Hsuan-Chao Hou, Louisiana State Univ. (United States); Yaser M. Banadaki, Southern Univ. and A&M College (United States); Safura Sharifi, Louisiana State Univ. (United States)

ABSTRACT - Raman scattering is a well-known technique for detecting and identifying complex molecular samples [1,2]. The weak Raman signals are enormously enhanced in the presence of a nano-patterned metallic surface next to the specimen [3,4]. This paper reports new techniques to obtain the nanostructures required for Surface Enhanced Raman Scattering (SERS) without costly and sophisticated fabrication steps, which are nanoimprint lithography (NIL), electrochemical deposition, electron beam induced deposition, and focus ion beam (FIB) [5-8]. In addition to its low cost, this research is focusing not only on boosting the strength of the Raman signal, but also on coupling a remote probe to a spectrometer via an articulated arm. 5 to 20 nm Au thicknesses of sputtered Au were deposited on etched household aluminum foil (base substrate) for vitro application. The Raman signal were caused by the Au deposition angles, Au deposition thicknesses, Au deposition positions and pre-etched times. In preliminary results, enhancement factors of 106 times were observed from SERS substrate for in vitro measurements. Moreover, the ability to perform in vivo measurements were demonstrated after removing the base aluminum foil substrate. This application allows Raman signals to be obtained from the surface or interior of opaque specimens. The nano-patterned gold may also be coupled in a probe to a remote spectrometer via an articulated arm. Rhodamine 6G and chicken specimens were employed for the biological measurements. This opens up Raman spectroscopy for use in a clinical environment.

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10167-14, Session 5

Optical and mechanical properties of cellulose nanopaper structures

Dimitrios Tsalagkas, Lindong Zhai, Hyun-Chan Kim, Jaehwan Kim, Inha Univ. (Korea, Republic of)

The main objective of this study is to prepare and investigate the optical and mechanical properties of the obtained cellulose nanopaper structures. Cellulose nanopapers are based on cellulose nanofibrils (CNFs) suspensions by imitating papermaking processes. Among the promising characteristics of these films, made of small diameter CNFs, are their high mechanical strength and transparency. Thus, cellulose nanopaper is a potential material on the fabrication of flexible, low cost, green nanotechnology products. In the present work, CNFs are extracted by means of aqueous counter collision (ACC) mechanical treatment of softwood and hardwood bleached kraft pulps. Thin sheet films of CNFs suspensions are obtained under vacuum filtration followed by drying the resulting hydrogels. Mechanical and optical properties of the fabricated nanopaper are investigated by using pull test and UV-vis spectrometer.

10167-15, Session 5

Mechanical and electrical properties of carbonized tea based cellulose composite films

Jayaramudu Tippabattini, Hyun-U Ko, Abdullahil Kafy, Yaguang Li, Jaehwan Kim, Inha Univ. (Korea, Republic of)

In the present investigation, carbonized tea-based cellulose composite films are fabricated via solution casting technique. The fabricated films chemical structure, morphology, crystallinity and thermal stabilities are characterized by using Fourier transform infrared spectroscopy, scanning electron microscopy, X-ray diffraction and thermogravimetric analysis. The effect of carbonized tea loading on the properties of the carbonized tea-based cellulose composite films is studied. The results are expected that the carbonized tea composite films show better mechanical properties, thermal stability and dielectric constant than the neat cellulose films.

10167-16, Session 5

Properties of TEMPO-oxidized cellulose nanofiber by using aqueous counter collision

Hai Van Le, Lindong Zhai, Jeong Woong Kim, Eun-Sik Choi, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Cellulose nanofiber (CNF) isolation from different resources influences the characteristics of the CNF. There are two methods in the isolation of CNFs, chemical and physical methods. This paper deals with a TEMPO-oxidation chemical method and aqueous counter collision physical method to isolate CNFs. TEMPO-oxidized cellulose nanofiber was isolated using an aqueous counter collision method from different cellulose resource including Softwood, Hardwood and Cotton linter resources. The CNFs properties were studied by a thermogravimetric analyzer, X-ray diffractometer, atomic force microscopy, transmission electron Microscopy and Fourier transform infrared spectrometer. The width of the isolated CNFs is in the range of 10 nm to 20 nm and the length of cellulose nanofibers is around 1000 nm. The CNFs show lower thermal degradation stability than the pristine cellulose resources. The isolated CNF from cotton linter has the highest crystallinity

index and thermal degradation stability in comparison with those from hardwood and softwood.

10167-17, Session 5

Feasibility study of cellulose nanofiber alignment by high DC magnetic field

Hyun-Chan Kim, Jinmo Kang, Seong-Mi Byun, Asma Akther, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Cellulose nanofiber (CNF) has taken center stage as a future material with high specific strength, specific modulus and environmentally friendly behavior. However, natural CNFs are so randomly oriented that once CNFs are used in composites, their mechanical properties are not the same as expected from the CNFs. Thus, CNF alignment is important in fabricating composites and fibers. Interestingly, CNFs have negative diamagnetic anisotropy. In the presence of high magnetic field, the fiber axis of CNF can be aligned perpendicular to the applied field. This paper reports a preliminary study of CNF alignment by high dc magnetic field. The CNF suspension is prepared by aqueous counter collision method and centrifugation. The CNF suspension is located in the high dc magnet and cured for a certain time. The alignment of CNF is investigated by scanning electron microscopy and X-ray diffractometer.

10167-18, Session 5

Study of heart-brain interactions through EEG, ECG, and emotions

Mouli Ramasamy, Vijay Varadan, The Pennsylvania State University (United States)

This article is an investigative attempt to study emotion based neurocardiology and the factors that influence this phenomena. The factors include: interaction between sleep EEG (electroencephalogram) and ECG (electrocardiogram), relationship between emotion and music, psychophysiological coherence between the heart and brain, emotion recognition techniques, and biofeedback mechanisms. Emotions contribute vitally to the mundane life and are quintessential to a numerous biological and everyday-functional modalities of a human being. Emotions are best represented through EEG signals, and to a certain extent, can be observed through ECG and body temperature. Confluence of medical and engineering science has enabled the monitoring and discrimination of emotions influenced by happiness, anxiety, distress, excitement and several other factors that influence the thinking patterns and the electrical activity of the brain. Similarly, HRV (Heart Rate Variability) widely investigated for its provision and discerning characteristics towards EEG and the perception in neurocardiology. Recent advances in neuroscience have established emotion and cognition as of independent and interacting modalities. Similarly, the communication between heart and brain has been widely investigated. The communication between emotion and cognition is centralized at the brain, however, the number of pathways from emotion to cognition centers is greater that the number of pathways from cognition to emotion centers. These variations and similarities are studies using HRV and electroencephalographic modalities.

10167-19, Session 6

Epidermal electronic systems for sensing and therapy *(Keynote Presentation)*

Nanshu Lu, The Univ. of Texas at Austin (United States)

Epidermal electronics is a class of noninvasive, skin-conformable, stretchable sensors and electronics capable of continuous and long-term physiological sensing and clinical therapy. The high cost of manpower, materials, vacuum equipment and photolithographic facilities associated with its manufacture limit the availability of disposable epidermal electronics. We have invented a cost and time effective, completely dry, benchtop “cut-and-paste” method for the green, freeform and portable manufacture of epidermal electronics within minutes. We have applied the “cut-and-paste” method to manufacture epidermal electrodes, hydration and temperature sensors, conformable power-efficient heaters, as well as cuffless continuous blood pressure monitors out of metal thin films, two-dimensional (2D) materials, and piezoelectric polymer sheets. As a demonstration, we will discuss four examples in this talk. The first will be submicron thick, transparent epidermal graphene electrodes that can be directly transferred to human skin like a temporary transfer tattoo and can measure electrocardiogram (ECG) with significantly reduced motion artifacts compared with conventional gel electrodes. The second will be a long-term electromyogram (EMG) sensor worn on human forearm for the quantification of muscle fatigue and recovery over the course of several days. The third will be a chest patch which houses both electrodes and pressure sensors for the synchronous measurements of ECG and seismocardiogram (SCG) such that beat-to-beat blood pressure can be inferred from the time interval between the R peak of the ECG and the AC peak of the SCG. The last example will be a highly conformable, low power consumption epidermal heater for thermal therapy.

10167-20, Session 7

Polymeric humidity sensor

Wei-Chih Wang, Univ. of Washington (United States) and National Tsing Hua Univ. (Taiwan); Yen-Tse Cheng, National Tsing Hua Univ. (Taiwan)

In this paper, we demonstrate an embedded polymeric humidity sensor. The device measures humidity via an induced electrical impedance change on a polymer based thin film consisting of a cellulose based composite. The sensor features fast response, small hysteresis and strong repeatability. The fabricated sensor is appropriate for wearable application from its compact and efficient design and can be incorporated into textile to allow for applications such as body fluid monitoring and other biometrics.

10167-21, Session 7

Poly ionic liquid based nano composites for smart electro-mechanical devices

Kumkum Ahmed, Ajit Khosla, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Conducting polymer composites become increasingly significant for variety of applications in electrical and mechanical devices. Poly (ionic liquid)s (PILs) achieved remarkable interest in this field for the unique properties of ILs with macromolecular architecture and added advantages in mechanical stability, improved processability, durability, and spatial controllability over the IL species. Carbon nanotube (CNT) as filler material to the matrix of PIL can achieve the desired composite material with improved electrical and mechanical properties. In this work we developed PIL-CNT nanocomposites by using quaternary ammonium type IL monomer and multiwall CNT. Their electromechanical and thermal properties have been studied and future possibilities of employing in electromechanical devices have been explored.

10167-23, Session 7

Design and microfabrication of a novel structure ultra-thin PDMS microfluidic chamber

Shuyu Wang, Stony Brook Univ. (United States)

The advancement of microfluidics calls for microfluidic chambers with thin

walls to reduce the addenda mass in some application fields. A method to easily manufacture thin PDMS microfluidic chamber with high repeatability was presented in this paper. We used two ultra-thick SU 8 mold (200um) with high aspect ratio to face each other in order to formulate the thin wall on three dimensions with precise control of the thickness. A detailed fabrication process and its parameters were also discussed in the paper. Finally, this novel method can be readily expanded to arrays for large scale production.

10167-24, Session 7

Photocatalysis of titanium dioxide-carbon nanotube composites with reversible superhydrophobicity and superhydrophilicity

Ta-I Yang, Shi-Hui Hong, Yu-Jhen Lin, Chung Yuan Christian Univ. (Taiwan); I-Hsiang Tseng, Feng Chia Univ. (Taiwan)

Titanium dioxide- carbon nanotube (TiO2-CNT) composites are promising for application of photocatalysis. Therefore, the aim of this study is to develop a TiO2-CNTcomposite with reversible superhydrophobicity and superhydrophilicity for use in self-cleaning application.

The amount of TiO2 precursor, the added water, and the reaction time were systematically studied to obtain a TiO2 layer with desired thickness coated on the surface of CNT. In addition, the heat-treatment was utilized to control the crystalline structure of TiO2 and the hydrophobicity and hydrophilicity of resulting TiO2-CNT composites. The photocatalytic activity of the developed composites was evaluated by the photodegradation of a methylene blue (MB) solution under the illumination of ultraviolet (UV) light at ambient temperature.

Experimental results demonstrated that a layer of anatase TiO2 with thickness of 21nm, 27nm, or 65nm was successfully coated on the surface of CNT. The resulting TiO2-CNT composites are superhydrophobic, which the water contact angles ranged from 143o to126o based on the thickness of TiO2 layers. After subjected to a UV light, they became hydrophilic with a water contact angle less than 50o . Furthermore, the water contact angle of these TiO2-CNT composites restored to their original values without UV exposure, confirming they were with reversible superhydrophobicity and superhydrophilicity. Moreover, the developed TiO2-CNT composites also exhibited the capability of photocatalytic degradation of methylene blue (MB).

10167-25, Session 8

Potential and progress in quantum technology for NASA missions *(Keynote Presentation)*

Sang H. Choi, NASA Langley Research Ctr. (United States)

Since the development of quantum physics in the early part of the 1900s, this field of study has made remarkable contributions to our civilization. Some of these advances include lasers, light-emitting diodes (LED), sensors, spectroscopy, quantum dots, quantum gravity and quantum entanglements. In 1998, the NASA Langley Research Center established a quantum technology committee to monitor the progress in this area and initiated research to determine the potential of quantum technology for future NASA missions. The areas of interest in quantum technology at NASA included fundamental quantum-optics materials associated with quantum dots and quantum wells, device-oriented photonic crystals, smart optics, quantum conductors, quantum information and computing, teleportation theorem, and quantum energetics. A brief review of the work performed, the progress made in advancing these technologies, and the potential NASA applications of quantum technology will be presented.

10167-26, Session 9

Metallic junction thermoelectric device simulations

Adam J. Duzik, National Institute of Aerospace (United States); Sang H. Choi, NASA Langley Research Ctr. (United States)

The desire for alternative energy sources has pushed thermal energy conversion in recent decades. Thermoelectric junctions made of semiconductors have existed in radioisotope thermoelectric generators for deep space missions, but are currently being adapted for terrestrial energy harvesting. Unfortunately, these devices are inefficient, operating at only 7% efficiency. This has driven efforts to make high figure of merit thermoelectric devices, which require a high electrical conductivity but a low thermal conductivity, two properties that contradict one another. Efforts to lower thermal conductivity have increased efficiency, but at the cost of power output, which relies on thermal heat flux to generate power.

An alternative setup is to use metallic junctions as thermoelectric devices rather than semiconductors. Metals have orders of magnitude more electrons and electronic conductivities higher than semiconductors, but thermal conductivity is higher as well. To evaluate the viability of metallic junction thermoelectrics, a two dimensional heat transfer MATLAB simulation was constructed to calculate efficiency and power output. High Seebeck coefficient alloys, Chromel (90%Ni-10%Cr) and Constantan (55%Cu-45%Ni), produced efficiencies of around 20-30%. These improvements were realized by controlling parameters such as the number of layers of junctions, lateral junction density, and junction sizes for both serial and parallel connected junctions.

10167-27, Session 9

Cellulose/graphene oxide composite for electrode materials of flexible energy devices

Abdullahil Kafy, Asma Akther, Md Imrul Reza Shishir, Jaehwan Kim, Inha Univ. (Korea, Republic of)

The appeal of portable electronic devices is increasing day by day which creates an increase in the demand for flexible and renewable energy storage devices. Hybrid materials can be used as renewable and flexible source of electrode material for this kind of devices. Organic–inorganic hybrid materials represent a creative substitute to design new materials and composites by accepting advantages of both materials. This paper reports the possibility of renewable cellulose and graphene composite as an electrode material for energy storage device such as supercapacitor. The morphology and structure of the nanocomposite are studied using scanning electron microscopy and Fourier transform infrared spectroscopy. The performance of the composite as supercapacitor electrode material is evaluated by cyclic voltammograms and galvanostatic charge-discharge curves.

10167-29, Session 9

Coupling effects by closely packed rectenna arrays

Kyo D. Song, Deidra Walls, Norfolk State Univ. (United States); Sang H. Choi, NASA Langley Research Ctr. (United States); Hargsoon Yoon, Norfolk State Univ. (United States)

The development of power transmission by microwave beam power harvesting attracts manufactures for use of wireless power transmission. Optimizing maximum conversion efficiency and obtaining high power

density are affected by many design parameters, making it difficult for researchers to figure out. Combining several rectennas in one array potentially aides in the amount of microwave energy that can be harvested for energy conversion. Closely packed rectenna arrays is the result of the demand to minimize size and weight for flexibility. This paper investigates how coupling between each dipole positively and negatively affects the microwave energy, harvesting, and the design limitations.

10167-31, Session 10

3D printing of protein molecules

Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Proteins molecules play many critical roles in our body. They have large and complex structures, and understanding of the relationship between their structures and biological functions is a crucial key for biology and medicines. At the resent, to conceptualize structures of proteins, we rely on computer graphics of their three-dimensional (3D) structure.

On the other hand, physical models can convey "intuitive" understanding, and that is really useful for education and even for peer discussion. The first author Kawakami invented a new molecular model called "Kawakami model", which is a soft, transparent handleable model, can be fabricated by 3D printing and transparent silicone resin.

A full-color printed amino acid chain structure is embedded in the silicone body. The silicone body represents the molecular surface of protein molecule. Users can simultaneously feel the molecular surface, view through the main chain structure, and even manually simulate molecular docking. This model is already commercialized and available upon request. So far Many Kawakami models have already been shipped and being used as effective discussion tools for the classroom/laboratory, exhibition in museums/institutes, and outreach activities. In this session, some Kawakami-model will be presented, and demonstration of "Hands-On" protein-ligand docking and protein-protein interaction will be performed.

10167-32, Session 10

Smart walking stick for blind people: an application of 3D printer

Faidur Rahman, Md. Allama Ikbal, Univ. of Rajshahi (Bangladesh); Md. Hasnat Kabir, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Blind people are physically disabled. It is matter of fact that they are neglected in the society even though it is not their fault. Sometimes they face a lot of problems in their daily life activities. On the other hand, they need help from someone during their movement or daily life activity. A prototype of smart walking stick has been designed and characterized for the people who are visually impaired. In this study, it was considered that the proposed system will alert visually-impaired people over the obstacles which are in front of blind people as well as the obstacles of the street such as manhole, when the blind people are walking in the street.

The proposed system was designed into two stages, i.e. hardware and software which makes the system as a complete prototype. Two ultrasonic sonar sensors were used to detect in front obstacle and street surface obstacle such as manhole. Basically the sensor transmits an electromagnetic wave which travels toward the obstacle and back to the sensor receiver. The distance between sensor and the obstacle is calculated by the received signal. The calculated distance value is compared with the pre-define value and determines whether the obstacle is present or not. The 3D CAD software was used to design the sensor holder. An Up-Mini 3D printer was used to print the sensor holders which were mounted on the walking stick. Therefore, the sensors were fixed in the right position. Another sensor was used for the detecting the water on the walking street. The performance for detecting the obstacles and water indicate the merit of smart walking stick.

10167-33, Session 10

3D gel printing and applications

Kazuyuki Sakai, Masato Wada, Kyuuichiro Takamatsu, Azusa Saito, Ajit Khosla, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

We has developed 3D gel printer from 8 years ago. Around two thousand years, high strength gels were invented by Japanese researchers1,2,3). However, it was difficult to process high strength gels (Fig. 1), because gel is soft material and complex synthesis procedures are needed. In SWEL, we develop new type of high strength gels (ICN4), P-DN5)), which can be used for 3D gel printer. Furthermore we developed two type 3D gel printer, "Bathtub type" and "Dispenser type" in Strategic Innovation promotion Program (SIP) supported by cabinet office, government of Japan. Figure 2 shows 3D models made by high strength gels. Not only 3D gel printer, we have studied another processing methods, using laser cutter, using mold. Figure 3 shows 3D gel printers. Another side of important specific of high strength gel is low friction. Taking this advantage, we have studied gel-sheet, gel-O-ring, and so on. The apparatus of Fig.4 is gel friction meter to measure friction and/or toughness of the gel. This is also supported by the national project named "Green Tribology Innovation Network" in the area of Advanced Environmental Materials, Green Network of Excellence (GRENE).

We will show samples made by high strength gels in the demo session.

10167-34, Session 10

Caterpilike: a soft-bodied 3D printed robot inspired by caterpillars

Takuya Umedachi, The Univ. of Tokyo (Japan)

Caterpilike is a soft-bodied 3-d printed robot inspired by caterpillars. Caterpillars are excellent living models to extract the mechanical and control design principles for soft-bodied robots, since they produce adaptive and resilient behaviors by orchestrating the large degrees of freedom in their bodies (no explicit skeletons) with small numbers of neurons. Compared with traditional robotic systems consisting of hard-rigid components, the robot generates crawling locomotion driven by a few actuators by exploiting the continuum large-deformation of the soft material. We believe that such body design is important to endow a robotic system to have high an affinity with our living and natural environments.

10167-35, Session 10

3D printing in social education: Eki-Fab and student PBL

Masato Makino, Azusa Saito, Mai Kodama, Kyuuichiro Takamatsu, Hideaki Tamate, Kazuyuki Sakai, Masato Wada, Ajit Khosla, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Additive manufacturing or 3D printer is one of the most innovative material processing methods. We are considering that 3D printing human resources would be needed in the world in the future. To educate the abilities of the digital fabrication, we have the public digital space "Eki-Fab" for junior and high school students, and Project Based Learning (PBL) class for bachelor course students.

Eki-Fab is held on Saturday in the 2nd floor of the Yonezawa train station. In the "Eki-Fab", anybody can study the utilizing of 3D printer and its related modeling technics under the instruction of staff in Yamagata University.

In the PBL class, we have the class every Thursday. The students get the techniques of the digital fabrication through the PBL.

10167-36, Session 10

3D printing for food

Mai Kodama, Azusa Saito, Masato Makino, Ajit Khosla, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

We have been developing a new food by using the 3D printer in cooperation with local companies. Now, we would like to introduce two types of new products was realized in this effort as shown in Fig.1 and Fig.2. Fig.1 is a jelly with the form of a carp. This jelly is melted if you soak it in the hot water, so you can eat it as a soup. Fig. 2 is a jelly with the form of a lantern. Since this jelly does not melt even at high temperatures, you can eat as warm jelly. These jellies were formed by molds made by using the 3D printer as shown in Fig. 3. We made the jellies with the form of a carp and a lantern, because locals likes carps and lanterns. Carp had often eaten at a local since a long time ago following economical instructions of the then governor. Because our local is a lot of snow the region, there is a festival to make a lot of snow lanterns. If the practical application of the 3D printer is advanced, everyone can make the original food easily, and everyone may enable obtaining enjoyment of eating.

10167-37, Session 10

Direct material weaving by G-code manipulation

Soko Koda, Hiroya Tanaka, Keio Univ. (Japan)

No Abstract Available

10167-38, Session 10

Polymer-based blood vessel models with micro-temperature sensors in EVE

Mizue Mizoshiri, Yasuaki Ito, Takeshi Hayakawa, Junpei Sakurai, Seiichi Ikeda, Fumihito Arai, Seiich Hata, Nagoya Univ. (Japan)

No Abstract Available

10167-64, Session PMon

Comparative study of classification algorithms for damage classification in smart composite laminates

Asif Khan, Heung Soo Kim, Dongguk Univ. (Korea, Republic of); Chang-Kyung Ryoo, Inha Univ. (Korea, Republic of)

This paper presents a comparative study of different classification algorithms for the classification of various types of inter-ply delaminations in smart composite laminates. Improved layerwise theory is used to model delamination at different interfaces along the thickness and longitudinal directions of the smart composite laminate. The input-output data obtained through surface bonded piezoelectric sensor and actuator is analyzed by the system identification algorithm to get the system parameters. The identified parameters for the healthy and delaminated structure are supplied as input data to the classification algorithms. The classification algorithms considered in this study are ZeroR, Classification via regression, Naïve Bayes, Multilayer Perceptron, Sequential Minimal Optimization, Multiclass-Classifier, and Decision tree (J48). The open source software of Waikato Environment for Knowledge Analysis (WEKA) is used to evaluate the classification performance of the classifiers mentioned above via 75-25 holdout and leave-one-sample-out cross-validation regarding classification accuracy, precision, recall, kappa statistic and ROC Area.

10167-65, Session PMon

Single molecule dynamics of polyproline by using AFM

Hironori Tamamushi, Masaru Kawakami, Ajit khosla, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Polyproline forms a unique structure, called polyproline-II helix(PPII) in water. PPII is known to be a rigid molecule in spite of no hydrogen bonds between backbone atoms, and to play an important role in biological functions such as formation of collagen structure and in the cell-adhesion. In this study, we carried out single molecule force spectroscopy of Polyproline with AFM(Atomic Force Microscope) and covalent immobilization of Polyproline molecule on gold substrate to evaluate the rigidity of PPII at single molecule level. We found that the force-extension curve of Polyproline shows a linear increase, which is unusual and not seen with others homo-polypeptide molecules. These results indicate that the high rigidity of Polyproline II helix can be explained by “enthalpic”, not “entropic” driven elasticity.

10167-66, Session PMon

Portable fiber-optic taper coupled optical microscopy platform

Weiming Wang, Yan Yu, Hui Huang, Dalian Univ. of Technology (China)

The fiber optic taper coupled CMOS has advantages of high sensitivity, compact structure and low distortion. So it is widely used in low light, high speed and X-ray imaging systems. In the meanwhile, the peculiarity of the coupled structure can meet the needs of the Microscopy Imaging. Toward this end, we developed a cellphone based microscope for the measurement of the human blood samples and. The platform, weighing 70 grams, is based on the existing camera module of the smartphone coupled with a fiber-optic array providing a magnification factor of ~6X. The top facet of the taper, on which samples are placed, serves as an irregular sampling grid for contact imaging. The magnified image of the sample, located on the bottom facet of the fiber, is then projected onto the CMOS sensor. This paper introduces composition of the portable medicine imaging system based on the optical fiber coupling, and theoretically analyzes optics coupling feasibility between the optical fiber taper and CMOS. We have developed an Android application including cell counting algorithm running on the smartphone for counting the blood cells and density, visualized through the screen of the smartphone. The image data and process results can either be stored on the memory or be transmitted to the remote medical institutions for the telemedicine. We validate the performance of this cell-phone based microscopy platform using human blood samples and test target, achieved comparable results to a standard bench-top microscope.

10167-67, Session PMon

Development of new eardrum-inspired acoustic transducers

Gi-Woo Kim, Inha Univ. (Korea, Republic of)

The eardrum or tympanic membrane (TM) in human auditory system has a curved conical shape with the apex pointing medially. It generally receives airborne sound waves collected by the outer ear, transforms them into mechanical vibrations in the eardrum, and eventually transmits the vibrations to the middle ear, which is similar with acoustic transducers such

as microphones. The dynamic and mechanical behavior of the tympanic membranes displays both linearity and viscoelasticity. In this study, besides these two features, nonlinearity, particular bistablility, inspired by curved (buckled) conical shaped of tympanic membrane is explored to develop high-performance acoustic transducers. In addition, a frequency response function analysis is performed based on the obtained experimental results, and the effect of stiffness of buckled membrane is explored.

10167-68, Session PMon

Miniaturized accelerometer made with ZnO nanowires

Sangho Song, Jeong-Woong Kim, Hyun-Chan Kim, Young-Min Yun, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Miniaturized accelerometer is required in many applications, such as, robotics, haptic devices, gyroscopes, simulators and mobile devices. ZnO is an essential semiconductor material with wide direct band gap, thermal stability and piezoelectricity. Especially, well aligned ZnO nanowire is appropriate for piezoelectric applications since it can produce high electrical signal under mechanical load. To miniaturize accelerometer, an aligned ZnO nanowire is adopted to implement active piezoelectric layer of the accelerometer and copper is chosen for the head mass. To grow ZnO nanowires on the copper head mass, hydrothermal synthesis is conducted and the effect of ZnO nanowire length on the accelerometer performance is investigated. Refresh hydrothermal synthesis can increase the length of ZnO nanowire. The performance of the fabricated ZnO accelerometers is compared with a commercial accelerometer. Sensitivity and linearity of the fabricated accelerometers are investigated.

10167-69, Session PMon

Morphology, thermal, and dielectric properties of Hybrid PVC/ MWCNT / barium titanate nanocomposites

Elizabeth Francis, Jayaramudu Tippabattini, Eun-Sik Choi, Inha Univ. (Korea, Republic of); Sabu Thomas, Mahatma Gandhi Univ. (India); Jaehwan Kim, Inha Univ. (Korea, Republic of)

Synergistic hybrid composite materials based on poly vinyl chloride (PVC) are developed by combining barium titanate with multiwalled carbon nanotubes (MWCNT). In the present study, we are reporting the dielectric behavior MWCNT- barium titanate based PVC hybrid nanocomposite films. The films are prepared with 0.5, 1, 3 wt. % of MWCNT and the hybrid nanocomposite films are prepared with 1:1 ratio of MWCNT-barium titanate via solution casting technique. The use of barium titanate along with MWCNT is to improve the dispersion and reduce the agglomeration of MWCNT in PVC. Morphological, thermal and dielectric properties of nanocomposites and hybrid nanocomposites were investigated. The PVC hybrid nanocomposite shows higher thermal stability than the PVC and PVC-MWCNT nanocomposites. Dielectric properties of the composites are measured by using an impedance analyzer. The dielectric constant of PVC, PVC-MWCNT nanocomposites and PVC hybrid nanocomposites below 3 wt. % of the nanofiller contained films are frequency in-dependent, but at 3 wt.% films dielectric constant is frequency dependent, which means that dielectric constant decreases with frequency.

10167-70, Session PMon

Design of an ultrasonic fingerprint sensor made of 1-3 piezocomposites by the finite element method

Yongrae Roh, Haejune Park, Kyungpook National Univ. (Korea, Republic of)

Over the past two decades, many researchers have studied how to capture an electronic image of a human fingerprint. Among these, capacitive fingerprint sensors are the ones most widely used in consumer electronics. The sensor consists of an array of capacitors. When a finger is placed on top of the sensor, skin creates a change in the capacitances. By measuring the difference between the capacitors contacting ridges and valleys, respectively, a fingerprint pattern can be recognized. However, capacitive fingerprint sensors are extremely sensitive to contamination and moisture on the finger. Ultrasonic fingerprint sensors offer a potential solution to this problem because the fingerprint's valleys and ridges are easily distinguished due to the great difference in their acoustic impedance. In this paper, a detailed study on the operation of the ultrasound fingerprint sensor was carried out by analyzing the amplitude and arrival time of the wave reflected by the fingerprint patterns. The fingerprint sensor was designed using a 1-3 piezocomposite material to take advantage of its low acoustic impedance and high electro-mechanical coupling factor.

Results of the finite element analysis (FEA) of the ultrasonic sensor structure showed that the recognition of distinctive amplitudes were possible only when the FEA models of the sensor had acoustic walls. On the other hand, the peak time measurement could distinguish the ridges and valleys regardless whether the sensor had acoustic walls or not.

10167-71, Session PMon

Creation of the gel low friction surface with surface machining

Masato Wada, Naoya Yamada, Ajit Khosla, Masato Makino, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

In the medical field and food manufacturing process, Personnel expenses and the production cost are reduced, it is shortened on the appointed date of delivery, and production rationalization is performed in every aspect. As for the part of slider in particular, the supplies which may give bad influence for the human body and environment are not a little used. In this study, it is aimed for a product made in wound of the low friction surface of the functionality gel which aimed at safety and the low cost to the human body by replacing the part of those parts with the functional gels. This technique cuts off gel with a CO2 laser, and it is from a method to do to make the low friction surface by doing texturing on a method to make the sliding surface and the gel surface. We let the section produce wounds at the low friction surface by I soaked the gel which we cut with laser material processing into pure water, and reaching the equilibrium swelling. In addition, the surface which performed texturing to the surface let you swell equally and measured a dynamical friction coefficient by a ball on disk friction examination and observed the surface by an optical microscope.

The dynamical friction coefficient of the low friction gel surface which we made by this technique compared anything with the gel surface which I did not process and showed about a one-third. In addition, we confirmed that an abrasion trace became extinct by the degree of the texturing.

By using this method , conveniently becomes possible to begin to create a low friction surface in the high-strength gel is estimated to transition to a steady slip by influence of Stick - Slip is reduced.

10167-72, Session PMon

Application of 3D printer to food

Mai Kodama, Azusa Saito, Ajit Khosla, Masato Makino, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

3D printer is used for various applications such as prototype of industrial products, figure and diorama. In recent years 3D printer is deployed on medicine and food, recently food 3D printer progress is remarkable. However food 3D printer has several problems such as small repertoire of material, less-accurate of modeling and difficult to use successfully. So we thought make a mold and application to food with high accuracy Fused Deposition Modeling (FDM) 3D printer.

Positive die is printed by 3D printer and negative die is produced by poured silicon into a positive die. A firm jelly is easily removed from negative die because it is very soft made of silicon. Fabricated two mold carp and snow lantern is precisely manufactured to detail. Both are used Japanese restaurant.

Carp jelly made from soy milk, dried carp and gelatin change carp-Nabe when heated. Snow lantern jelly made from beef consomme soup is able to eat warm jelly. Difference between the two jellies for heating is coagulant. Gelatin made from collagen contained in pig or cow skin melt at 25 °C for jelly. But agar made from marine alga not melt at 70 °C for jelly.

Fabricated mold designed using free 3D CAD and anyone uses well. Use of 3D printer, can be make original food easily and enable obtaining enjoyment of eating.

10167-73, Session PMon

High-sensitive terahertz sensor based on an asymmetric split-loop resonator type metamaterials

Han-Cheol Ryu, Sahmyook Univ. (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We propose a high-sensitive sensor based on an asymmetric split-loop resonator (ASLR) type metamaterial operating in the terahertz frequency range. Structural asymmetricity of the ASLR makes the asymmetric Fano resonance which has a high quality factor compared to the symmetric resonance. The variations of the resonant frequency, transmission coefficient, and quality factor of the ASLR in the Fano resonance were analyzed according to the variation of the structural asymmetricity of it. And the surface current density on the ASLR was calculated to analyze the main cause of the variation of transmission characteristics of it. The surface current of ASLR in the Fano resonance showed trapped or quadrupole mode which has a low radiation loss. Therefore, the ASLR operating in the Fano resonance has a high quality factor. The ASLR having a high quality factor can be applied to a high sensitive sensor system because of the high field concentration in the gaps of ASLR metamaterial. The sensitivity of the ASLR was optimized by control of the asymmetricity of the ASLR. The performance of the proposed sensor based on the metamaterial was confirmed by characterizing the doped protein thin films having various doping concentration and thickness using terahertz time-domain spectroscopy. The resonant frequency of the metamaterial was high-sensitively shifted by the variation of the doping concentration and the thickness of the thin films. The proposed high-sensitive sensors based on the terahertz ASLR metamaterial could be used for the detection of biological and chemical sensing applications.

10167-74, Session PMon

Effects of heath treatments and UV exposures on mechanical properties of 3D printed acrylonitrile butadiene styrene specimens

Shawn M. Hughes, Mohammed Alamir, Brian Neas, Ramazan Asmatulu, Wichita State Univ. (United States)

Over the last few years, tremendous amount of research efforts has been conducted on 3D printing materials, methods and systems. Various 3D printer materials in different size, shape and geometry can be used for advanced designs, modeling, and manufacturing for different industrial applications. In the present study, dog bone shape specimen was designed via a CATIA CAD model, and then printed by a 3D printer using a polymeric material (acrylonitrile butadiene styrene - ABS). Some of the prepared samples were heat treated at 40 ºC, 60 ºC, and 80 ºC for 30 minutes, while the others were exposed to the UV light in a chamber for 0, 5, 10, 15 and 20 days. The surface and mechanical properties of the conditioned samples were determined using water contact angle and tensile test units, respectively. The test results indicated that the heat treatment process increased the mechanical properties; however, the UV exposure tests significantly reduced the water contact angle and tensile properties of the samples. During these studies, undergraduate engineering students were involved in the tests, and gained a lot of hands-on research experiences.

10167-75, Session PMon

Encapsulation of natural ingredient for skin protection via nanoemulsion process

Eylem Asmatulu, Naif Alzahrani, Vinay Patil, Aybala Usta, Adeesha Vanderwall, Wichita State Univ. (United States)

Many of the sunscreens are used during the hot summer time to protect the skin surface. However, some of ingredients in the sunscreens, such as oxybenzone, retinyl palmitate and synthetic fragrances including parabens, phthalates and synthetic musk may disrupt the cells on the skin and create harmful effects to human body. Natural oils may be considered for substitution of harmful ingredients in sunscreens. Many natural oils (e.g., macadamia oil, sesame oil, almond oil and olive oil) have UV protective property and on top of that they have natural essences. Among the natural oils, olive oil has a long history of being used as a home remedy for skincare. Olive oil is used or substituted for cleanser, moisturizer, antibacterial agent and massage reliever for muscle fatigue. It is known that sun protection factor (SPF) of olive oil is around eight. There has been relatively little scientific work performed on the effect of olive oil on the skin as sunscreen. With nanoencapsulation technique, UV light protection of the olive oil can be extended which will provide better coverage for the skin throughout the day. In this study, natural olive oil was incorporated with DI water and surfactant (sodium dodecyl sulfate - SDS) and sonicated using probe sonicators. Sonication time, and concentrations of olive oil, DI water and surfactant were investigated in detail. The produced nanoemulsions were characterized using scanning electron microscopy, dynamic light scattering, and UV-Vis spectroscopy. It is believed that the nanoencupsulation of olive oil could provide better skin protection by slow releasing and deeper penetration of the nanoemulsion on skin surface. Undergraduate engineering students were involved in the project and observed all the process during the laboratory studies, as well as data collection, analysis and presentation. This experience based learning will likely enhance the students' skills and interest into the scientific and engineering studies.

10167-39, Session 11

Micro-nano sensors, systems, and devices for precision medicine *(Keynote Presentation)*

Ajit Khosla, Yamagata Univ. (Japan)

Precision medicine (PM) is a medical model that proposes the customization of healthcare, with medical decisions, practices, and/or products being tailored to the individual patient. by far the most encouraging and challenging aspect of precision medicine is the meaningful use of technology such as the wearable sensors used for vital sign monitoring. Wearable sensors should be flexible, shape conformable, stretchable, excellent adhesion to body/skin, and should retain their ability to reliably record biopotential signals continuously over a period of time. Hence, not only new sensing materials need to developed but also new flexible and stretchable substrates. Previously, we had reported development of various sensing materials which can be micro and nano fabricated [1-14].

This talk focuses on development on new sensing materials for wearable sensors and devices for precision medicine, healthcare and environmental monitoring which make an excellent contact with body/skin which can be micro-nano fabricated

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10167-40, Session 12

Review 3D printing technologies for micro-nano systems

Ajit Khosla, Yamagata Univ. (Japan)

No Abstract Available

10167-41, Session 12

Liquid-in-gel 3D printed droplet-based materials

Elio Challita, Joseph S. Najem, Eric C. Freeman, Donald J. Leo, The Univ. of Georgia (United States)

The engineering and construction of biological tissue mimics remains a primary challenge in synthetic biology. Achievement of functional protocell-based tissues depends on the ability to mass produce robust and durable aqueous droplets, the ability to precisely position the droplets (protocells), and the ability to connect the droplets and to allow them to interact. Mass production and precise positioning may be achieved via 3D printing, and therefore, the development of a 3D printer capable of printing large numbers of aqueous droplets in oil is required. Herein, we present the design and development of a 3D printer for the production of droplet-based 3D materials. This is achieved by modification of a commercially available 3D printer. The hot head that comes with the printer is replaced with a lab-made piezoelectric droplet generator. The droplet generator consists of an acrylic chamber capable of containing a certain volume of an aqueous solution. To generate a droplet, a pulse is applied to the droplet generator and due to vibrational shocks 100 μm-droplets are released into bulk oil. Upon release of the droplets in the oil, which contains DPhPC lipids, a lipid monolayer forms at the water-oil interface of each droplet. Neighboring droplets are connected by means of lipid bilayers, which could also host various types of biomolecules. A ten-by-ten-by-three array of aqueous droplet is printed in a bath of temperature-sensitive organogel consisting of hexadecane and SEBS triblock copolymer. Upon cooling, the organogel solidifies to form a liquid-in-gel tissue-like material.

10167-42, Session 12

Inkjet-printed micro air flow sensor

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Printed organic sensors on flexible substrates have generated great interest due to their flexibility and low cost manufacturing. Methods such as inkjet printing, screen printing, etching or flexography are among many that have been used for the production process. In this paper, we report the fabrication and characterization of a free-standing, high aspect ratio PEDOT:PSS micro cylinder (20 um in diameter and 7 mm long) flow sensor printed by an inkjet process. Preliminary results from the fabricated sensor will be presented and future applications discussed.

10167-44, Session 13

Military efforts in nanosensors, 3D printing, and imaging detection

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A team of researchers and support organizations, affiliated with the Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC), has initiated multidiscipline efforts to develop nano-based structures and components for advanced weaponry, aviation, and autonomous air/ground systems applications. The main objective of this research is to exploit unique phenomena for the development of novel technology to enhance warfighter capabilities and produce precision weaponry. The key technology areas that the authors are exploring include nano-based sensors, analysis of 3D printing constituents, and nano-based components for imaging detection. By integrating nano-based devices, structures, and materials into weaponry, the Army can revolutionize existing (and future) weaponry systems by significantly reducing the size, weight, and cost. The major research thrust areas include the development of carbon nanotube sensors to detect rocket motor off-gassing; the application of current methodologies to assess materials used for 3D printing; and the assessment of components to improve imaging seekers. The status of current activities, associated with these key areas and their implementation into AMRDEC's research, is outlined in this paper. Section #2 outlines output data, graphs, and overall evaluations of carbon nanotube sensors placed on a 16 element chip and exposed to various environmental conditions. Section #3 summarizes the experimental results of testing various materials and resulting components that are supplementary to additive manufacturing/fused deposition modeling (FDM). Section #4 recapitulates a preliminary assessment of the optical and electromechanical components of seekers in an effort to propose components and materials that can work more effectively.

10167-45, Session 13

Magnetic nanotubes for drug delivery

Mouli Ramasamy, Vijay Varadan, The Pennsylvania State University (United States)

Magnetic nanomaterials, especially nanoparticles and nanotubes, are among the most widely used nanomaterials for biomedical applications, and they are also the most promising nanomaterials for clinical treatments. The non-fouling, non-toxic, large surface area of nanotubes makes them a lucrative material for use in biosensors. Nanotubes provide multiple advantages over other nanomaterials, like quantum dots, nanowires, nanopores, etc., for use in biological sensors. The electrical conductivity couple with their bio friendly natures of the nanotubes render them to be a candidate for use in implantable sensors and devices. The inert nature and yet multiple functional chemistries of CNTs makes them suitable candidate to be used in various targeted biological systems. Also, their hollow nature makes them a prime candidate for drug delivery systems, high density pathogen binding and detection systems, and cell separation studies. By combing the salient features of existing silicon technology with the properties of CNTs and MNTs, we would be able to explore a lot of new medical devices and sensors. The nanotubes could also be used to optically detect biological entities in laboratory setups. The current state of the art in nanotube and biotechnology research has only scratched the surface. This paper is an investigative attempt to study the fundamentals of nanomedicine and magnetic nanomedicine, basic requirements for the biomedical applications, the properties and the biomedical applications of magnetic nanoparticles and nanotubes, and the challenges and approaches for targeted drug delivery with controlled release

10167-30, Session 14

Energy storage crystalline gel materials for 3D printing application

Yuchen Mao, Yamagata Univ. (Japan) and Donghua Univ. (China); Takuya Miyazaki, Jin Gong, Yamagata Univ. (Japan); Meifang Zhu, Donghua Univ. (China)

Phase change materials (PCMs), which can absorb or release the enthalpy of phase changes in certain temperature ranges, are considered one of the most reliable latent heat storage and thermoregulation materials. It is a highly efficient and environmentally friendly way to use residual heat and store the renewable energy. PCMs have been successfully used in the fields of solar energy, aerospace and aviation, environmental control, textiles and food freshness-keeping. Our purpose is to create a phase change thermoregulation gel objects with complex structure from reactive solution directly. Energy storage vinyl monomers are used to synthesize copolymer gels by light curing. These copolymer gels have crystalline side-chain for providing energy storage capacity. The crosslinking structure of the copolymer can protect the crystalline micro-area maintaining the phase change stable in service and improving the mechanical strength. By selecting different monomers and adjusting their ratios, we can design the chemical structure and the crystallinity of gels, which in further affect their properties, such as strength, flexibility, thermal absorb/release transition temperature, transparency and the water content. Using the light-induced polymerization 3D printing techniques, we synthesize the energy storage gel and shape it on a 3D printer at the same time. By optimizing the 3D printing conditions, including layer thickness, layer curing time and light models, etc., the dimensional accuracy of shaped objects are improved. The crystal behavior, mechanical properties and energy storage capacity of the 3D printed crystalline gels are investigated in this paper.

10167-46, Session 14

Simulation of 3D food printing extrusion and deposition

Masato Makino, Yamagata Univ. (Japan); Daisuke Fukuzawa, SIMLON Co., Ltd. (Japan); Takahiro Murashima, Tohoku Univ. (Japan); Hidemitsu Furukawa, Yamagata Univ. (Japan)

The food printer process is simulated by Smoothed Particle Hydrodynamics Method.

In the food printer, the liquid-like food is extruded from syringe and deposited on the substrate to make an arbitrary shaped food. The printing process and the final shape of produced food depend on viscosity, non-

Newtonian property of the food and injection speed.

In this study, we develop and simulate the extrusion and deposition process using one of the particle methods, Smoothed Particle Hydrodynamics Method. The height and width of the produced products are examined in various environment.

10167-47, Session 14

Development of gel dosimeter with 3D printer

Kazuyuki Sakai, Yamagata Univ. (Japan)

Gel dosimeter has been promising method to measure 3D absorbed dose distribution. Recently, gel dosimeter has also valued to verify dose distribution around bone and/or metallic implants in body.We make artificial organs by using 3D gel printer and implant bones and/or metallic stent to the organs for dosimetry. In this presentation, the experiment and study status are reported.

10167-48, Session 14

Direct G-code manipulation for 3D material weaving

Soko Koda, Hiroya Tanaka, Keio Univ. (Japan)

The process of conventional 3D printing begins by first build a 3D model, then convert to the model to G-code via a slicer software, feed the G-code to the printer, and finally start the printing. The most simple and popular 3D printing technology is Fused Deposition Modeling (FDM). However, in this method, the printing path that the printer head can take is restricted by the G-code. Therefore the printed 3D models with complex pattern have structural errors like holes or gaps between the printed material lines. In addition, the structural density and the material's position of the printed model are difficult to control. In this study, we focused on the G-code editing for making a more precise and functional printed model with both single and multiple material. An smart G-code editing realizes not only the elimination of structural errors, but also the specific positions control of the printing path to archive the weaving structure. Thus the special G-code editor is proposed, and it can print the models with different stiffness by the controlling the printing density of Polylactic acid (PLA). This result indicates that editing the G-code can control the infilling density and change the physical properties of printed model. In particular, the multi-material 3D printing has more possibility for expanding the physical properties by combining each material and its G-code editing. These results provide more creative and functional 3D printing techniques.

10167-49, Session 14

The flexibility controlling study for 3D printed splint

Jianyou Li, Hiroya Tanaka, Keio Univ. (Japan)

The idea of 3D printed splint for fracture injury have been appeared for few years, and the splint's advantages, such as light weight, ventilation, aesthetic features and water-proof can highly increasing the daily comfortableness during the patient treatment. Somehow, current FDM material's hardness would cause critical skin friction and allergy, and not suitable for necessary sensitisation and haemolytic tests of FDA certification. Therefore, many following ideas turned to pursue combining other material or embedded sensors, but these new developments may cause more difficulty in the manufacturing and can't help 3D printed splint to overcome from the concept stage.

In this study, a printed prototype of splint made by the flexible filament is tested, two main techniques to control the infilling density and printing temperature are verified to make splints that match the above wearable requirements. The first printing technique can gradually increase the infilling cross density in each layer from splint outside to inside, and that would turn the partial strength from hard to flexible. Besides, increasing printing temperature can also achieve stronger crystal hardness after cooling, and this skill is also applied on outside printing parameters. Therefore, such structural can provide high strength in outside surface to keep the critical immovable function, and give flexible touch of inside surface to decrease friction on the patient's skin. This technological approach can replace the common solution to make multiple parts by different materials and assembly, and that can reduce the time consuming, possible failure and complex design of multiple parts.

10167-50, Session 14

The generative system of combinable natural structure

Yinghsiu Huang, National Kaohsiung Normal Univ. (Taiwan); Hiroya Tanaka, Keio Univ. (Japan)

Therefore, the objective of this paper is to construct a combinable system, derived from natural objects, behavior, structure...etc. By observing and analyzing natures, the composition rules will be represented by generative software in virtual world, such as grasshopper. Therefore, the generative system could derive different forms based on the rules of natural combinations. Moreover, the elements with the joints of each composition will also be generated for 3D-printers; however, the technology of 3D printing could only print out objects with fixed softness of materials. Thus, the joints of each component will not be flexible to assemble. In this research, different softness of materials will be printed in one component by controlling temperatures of printing head based on different functions of each part. By doing so, hard part of component will become the main structure of natural forms, and soft part will be the joint to combine other component. Consequently, this paper is not only proposing the generative system of natural forms, but also printing out different softness parts of objects by modifying G-Code to control temperatures while printing 3D objects.

10167-51, Session 14

4D printing of active shape-changing structures with shape memory polymers

Hongqiu Wei, Qiwei Zhang, Yongtao Yao, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Shape memory polymers (SMPs), a typical class of smart materials, have been witnessed significant advances in the past decades. Based on the unique performance to recover the initial shape after going through a shape deformation, the applications of SMPs have aroused growing interests. However, most of the researches are hindered by traditional processing technologies which limit the design space of SMPs-based structures. Three-dimension (3D) printing as an emerging technology endows design freedom to manufacture materials with complex structures. In present article, we show that by employing direct-write printing method; one can realize the printing of SMPs to achieve 4D active shape-changing structures. We first fabricated a kind of 3D printable polylactide (PLA)-based SMPs and characterized the overall properties of such materials. Results demonstrated the prepared PLA-based SMPs presenting excellent shape memory effect. In what follows, the rheological properties of such PLA-based SMP ink during printing process were discussed in detail. Finally, we designed and printed several 3D configurations for investigation. By combining 3D printing with shape memory behavior, these printed structures achieve 4D active shape-changing performance under heat stimuli. This research presents a high flexible method to realize the fabrication of SMP-based 4D active shape-changing structures, which opens the way for further developments and improvements of high-tech fields like 4D printing, soft robotics, micro-systems and biomedical devices.

10167-52, Session 14

SAW based micro- and acousto- fluidics in biomedicine

Mouli Ramasamy, The Pennsylvania State University (United States); Prashanth Kumar, Pennsylvania State Univ. (United States); Vijay Varadan, The Pennsylvania State University (United States)

Microfluidics is a promising area with immense potential that can cater to the needs of self-assembly needs of biomolecules. Combination of microfluidics with acoustic waves can be used to regulate the assembly by modulating the channel of the device, size of the molecules and by varying the power and wavelength of the acoustic waves. These devices are capable of segregating and assembling structures based on particle size, density, compressibility and structural orientation. The principle of operation is rather simple: the inter-digital electrodes (IDT) arranged in the required orientation generates standing surface acoustic waves (SSAW), and the intersection of two or more of these standing waves are used to manipulate the arrangement of molecules. Similarly, optics can be coupled with microfluidics to study the patterning and assembly by introducing fluorescence imaging techniques. This review is attempt to study the various principles behind SAW based acoustofluidics and microfluidics

10167-53, Session 14

Design of the mechanical properties of the gel by the 3D gel printer "SWIM-ER"

Azusa Saito, Takafumi Ota, Taishi Tase, Kyuichiro Takamatsu, Masaru Kawakami, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gel organ models with realistic touch are needed by doctors because they improve the quality of the practice of surgical operation and the education of medical students. Actual organs have portions with different hardness such as aneurysms or swellings. We were considering how to design the hardness distribution of the gel by the 3D gel printer.

10167-54, Session 14

Synthesis of crystalline gels on a light-induced polymerization 3D printer

Jin Gong, Yuchen Mao, Takuya Miyazaki, Yamagata Univ. (Japan); Meifang Zhu, Donghua Univ. (China)

3D printing, also knows as Additive Manufacturing (AM), was first commercialized in 1986, and has been growing at breakneck speed since 2009 when Stratasys' key patent expired. Currently the 3D printing machines coming on the market can be broadly classified into three categories from the material state point of view: plastic filament printers, powder (or pellet) printers, film printers and liquid photopolymer printers.

Much of the work in our laboratory revolves around the crystalline gels. We have succeeded in developing them with high toughness, high flexibility, particularly with many functions as shape memory, energy storage, freshness-retaining, water-absorbing, etc. These crystalline gels are synthesized by light-induced radical polymerization that involves light-reactive monomer having the property of curing with light of a sufficient energy to drive the reaction from liquid to solid. Note that the light-induced polymerized 3D printing uses the same principle. To open up the possibilities for broader application of our crystalline functional gels, we are interested in making them available for 3D printing. In this paper, we share the results of our latest research on the 3D printing of crystalline gels on light-induced 3D printers.

10167-55, Session 14

Direct-writing of copper-based micropatterns on polymer substrates using femtosecond laser reduction of copper (II) oxide nanoparticles

Mizue Mizoshiri, Yasuaki Ito, Junpei Sakurai, Seiichi Hata, Nagoya Univ. (Japan)

Copper (Cu)-based micropatterns were fabricated on polymer substrates using femtosecond laser reduction of copper (II) oxide (CuO) nanoparticles. Laser reductive sintering of metal oxide nanoparticles enables to fabricate metal micropatterns in the atmosphere using laser-induced thermochemical reduction of metal oxide to metal. In this presentation, CuO nanoparticle solution, which consisted of CuO nanoparticles, ethylene glycol as a reductant agent, and polyvinylpyrrolidone as a dispersant, was spin-coated on poly(dimethylsiloxane) (PDMS) substrates and was irradiated by focused femtosecond laser pulses to fabricate Cu-based micropatterns. Femtosecond laser system operating with a pulse duration of 120 fs, wavelength of 780 nm, and repetition frequency of 80 MHz, was used for laser-induced thermochemical reduction of CuO nanoparticles. When the laser pulses were raster-scanned onto the solution, CuO nanoparticles were reduced and sintered. Cu-rich and copper (I)-oxide (Cu2O)-rich micropatterns were formed at laser scanning speeds of 15 mm/s and 0.5 mm/s, respectively, and at a pulse energy of 0.54 nJ. Cu-rich electrically conductive micropatterns were obtained without significant damages on the substrates. On the other hand, Cu2O-rich micropatterns exhibited no electrical conductivity, indicating that microcracks were generated on the micropatterns by thermal expansion and shrinking of the substrates. We demonstrated a direct-writing of Cu-rich micro-temperature sensors on PDMS substrates using the foregoing laser irradiation condition. The resistance of the fabricated sensors increased with increasing temperature, which is consistent with that of Cu. This direct-writing technique is useful for fabricating Cu-polymer composite microstructures.

10167-56, Session 15

Photo-electronic current transport in back-gated graphene transistor

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In this work, we have studied photo-electronic current transport in a back-gated graphene field-effect transistor. Under light illumination, band bending at the met-al/graphene interface develops a build-in potential [1] which generates photonic current at various back-gate biases. A typical MOSFET type back-gated transistor structure uses a monolayer gra-phene as a channel formed over Silicon Dioxide/Silicon substrate and Ti/Pd source and drain. Back gate bias is applied from -16V to +10V. It is shown that the photo-electronic current consists of cur-rent contributions from photoelectric and photo-thermoelectric effects. Under photoelectric effect, change in Fermi level of graphene near metal/graphene interface develops a built-in potential close to 0.1eV which can be increased or decreased depending upon back-gate bias. This changes the conductivity of graphene [2]. Under photo-thermionic effect, a temperature gradient is formed which develops into an equivalent voltage due to diffusion of charge carriers and can be calculated from Seebeck Coefficient and treating light as a radial wave [3]. Under low laser power source, the photo-thermoelectric effect is small enough to be neglected, while under high laser power source, this effect becomes noticeable though still small. A maximum external responsivity close to 0.00083A/W is achieved at 30?W power (laser source) and 633nm wavelength. The model is in good agreement with the reported experimental results [4].

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10167-57, Session 15

Graphene field effect transistor for generating on-chip thermoelectric power

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Graphene is a promising material for integrated circuit design due to its large surface-to-volume ratio, high carrier mobility, high carrier density, high thermal conductivity, and high mechanical strength [1]. The nanoscale transistors have small power consumption, but large power density in the integrated circuits wastes energy in the form of heat at nanometer dimension. Graphene can be useful for monitoring the die temperature [2] or converting the dissipated heat into electric power for integrated circuits [3].

Recent studies show the potential application of graphene as a promising thermoelectric material [3, 4]. In this paper, we have developed full Boltzmann transport equation (BTE) solver to explore the feasibility of graphene FET for generating thermoelectric power (TEP). We found that thermoelectric power increases with increase in applied gate voltage and the peaks has strong dependence on the scattering mechanisms close to charge neutrality point. For 100K temperature difference between source and drain electrodes, the peak TEP value of ~130μV/K is measured for graphene FET with 1μm ballistic channel. However, the peak TEP can be increased to ~180μV/K for Graphene on SiO2 substrate due to the strong contribution of surface polar phonon (SPP) and elastic scattering. Further increase in TEP value requires phonon engineering to reduce the thermal conductivity of graphene without significant reduction in its thermoelectric power and electrical conductivity [5].

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10167-58, Session 15

Phononic dispersion of graphene using atomistic-continuum model and spectrally formulated finite element method

Sushovan Mukherjee, Srinivasan Gopalakrishnan, Indian Institute of Science (India)

Grapahene is a two dimensional allotrope of carbon. Since the onset of current century, particularly, upon successful exfoliation of single layer graphene, it has received significant research attention because of some of the extreme mechanical, thermal, electromagnetic and optical properties it exhibits. As various applications of graphene have been envisioned and their realizations attempted, dynamic characteristics of graphene also became an extremely important field of study. Based on solid state physics and first principle analysis, dispersion relationship of graphene has been computed using various methods. Some of these methods rely on various interatomic potentials and force-fields. An approximate technique of mechanical characterization involves atomistic-continuum modeling of carbon carbon bonds in graphene and its rolled 1D form carbon nanotube. In this technique, the carbon-carbon bonds are modeled as 1D frame elements. The equivalence of energies in various modes of the actual structure and the equivalent mechanical system has led to specification of various model parameters. Here, based on atomistic continuum method, we attempt to compute the dispersion relationship accounting for the bonded interactions and the next nearest non-bonded interactions. For that purpose we use frequency domain spectral finite element method with pointed inertial components. It has been shown that it is possible to obtain the dispersion relationship close to the one computed using ab-initio method.

10167-59, Session 16

Mechanical property characterization of cellulose nanofiber by atomic force microscopy

Lindong Zhai, Jeong-Woong Kim, Sangho Song, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Cellulose nanofibers (CNFs) are strong natural fibers and they are renewable, biodegradable and the most abundant biopolymer in the world. To study and apply CNFs in many areas, understanding of their mechanical properties is very important. However, there are not many reports of CNF's mechanical properties directly measured because of its small size of CNFs, and these values are widely varied depending on the resources and measurement methods. Thus, this paper investigates the mechanical properties of CNFs by using an atomic force microscope. The CNFs are generated by an aqueous counter collision method. The CNFs are nano-sized to 20-50 nm under 200MPa high pressure. The CNF suspension is diluted with deionized water and sprayed on a silicon groove substrate. By performing a nanoscale 3-point bending test using the atomic force microscopy, bending stiffness of the CNF is found and its elastic modulus can be obtained by calculating the fiber deflection and several parameters. The elastic moduli obtained from different resources of cellulose such as hardwood, softwood and cotton are investigated.

10167-60, Session 16

Elastic wave propagation in in-homogenous peridynamic bar

Venkata Mutnuri, Srinivasan Gopalakrishnan, Indian Institute of Science (India)

Peridynamics [1] is recently proposed non-local continuum theory for the study of solids with discontinuities, such as, heterogeneity and cracks. Dispersion law was earlier established for a constant micro-modulus function, showing the similarities with other non-local models [2]. It was shown that peridynamics to be a general theory in comparison to stress and strain gradient models. It was also shown that peridynamic bar to be a low-pass filter with existence of an escape frequency. Further, at certain frequencies waves are shown to propagate with negative group speeds. These characteristics were shown to be an exact match to that of the long-range interactions of periodic one dimensional spring-mass lattice model.

In this study, dispersion curves for in-homogenous micro-modulus function within the horizon will be presented. Variations of the type linear and non-linear, for example, exponential and sinc functions, for the micro-modulus function within the horizon will be considered. In the linear case, it is observed from the group speeds behavior that, not all micro-modulus functions are stable. Yarnell et. al., [3] have shown a close relationship of experimental phonon dispersion curves to that of long-range interaction of lattice dynamics for Aluminum. Using this dispersion inter-relationships between the peridynamics, lattice dynamics and the experiment, a study is being carried out to establish peridynamic material parameters: horizon length and micro-modulus function.

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10167-61, Session 16

Band structure computation of polygonal solid-solid phononic crystal with features using frequency domain spectral superelement method

Sushovan Mukherjee, Srinivasan Gopalakrishnan, Indian Institute of Science (India)

Phononic crystals are synthetic materials with a periodic structure having spatial variations of elastic and inertial properties of the constituent materials. Studies on phononic crystals are aimed at developing, primarily, devices and potentially, bulk structural material- with engineered acoustic/elastic properties. Structures consisting of elements along the sides of a space filling polygonal tessellation, made of multiple materials, can constitute solid-solid phononic crystal. Coupled with various inclusions-particularly at joints, and features like holes, these type of phononic crystals show rich and varied band structure phenomenon.

We use a frequency domain spectral superelement method based technique along with Bloch theory to efficiently calculate the band structures of such phononic crystals. This method relies on frequency domain spectral finite element method to model members as frame elements behaving as 1D waveguide, contributing to the efficiency, while complex joints and inclusions are modeled using conventional finite element- improving the accuracy. We particularly investigate hexagonal honeycombs to assess the impacts of joint elasticity and inertia and implications of circular and elliptical holes on the band gap behavior.

10167-62, Session 16

A numerical model for the prediction of the electrical conductivity of nanofilled polymeric matrices

Monica Ciminello, Antonio Concilio, Salvatore Ameduri, Ctr. Italiano Ricerche Aerospaziali (Italy)

This work describes a numerical approach aimed at predicting the electrical conductivity of polymeric matrices filled with carbon nano-tubes (CNTs). The tunneling effect was modeled through a finite element approach. Each particle was schematized as a cluster of nodes connected by highly conductive elements, in compliance with the large conductivity of the CNTs. When two particles are in tunneling condition, a link was realized, whose electrical resistance was computed through a formula, involving, among the others, parameters like the mutual distance and the tunnel cross section area. The resulting system, a truss structure network contained within a cubic polymeric matrix, was then solved through a thermal analogy. The inward and outward currents passing through two opposite cube faces were simulated by applying thermal fluxes of opposite sign; the voltage drop caused by the global resistance was then estimated through a steady heat transfer analysis, giving the temperature gradient between the opposite faces. The ratio between the voltage (temperature) drop and the inward-upward current (thermal flux) was then assumed as resulting global resistance of the cube. A parametric investigation was finally performed, finding out the dependence of the gage factor (strain vs resistance variation) on CNT concentration and aspect ratio parameters.

10167-63, Session 16

Nanomechanics of carbon nanotubes

Mouli Ramasamy, Vijay Varadan, The Pennsylvania State University (United States)

This review focusses on introducing the mechanics in carbon nanotubes (CNT), and the major applications of CNT and its composites in biomedicine. It emphasizes the nanomechanics of these materials by reviewing the widely followed experimental methods, theoretical models, simulations, classification, segregation and applications of various modalities of CNT. First, several mechanical properties contributing to the classification of the CNT, for various biomedicine applications, are discussed in detailed to provide a cursory glance at the uses of CNT. The mechanics of CNT discussed in this paper include: elasticity, stress, tension, compression, and nano-scale mechanics. In addition to these basic properties, a brief introduction about nanoscale composites is given. Second, a brief review on some of the major applications of CNT in biomedicine including drug delivery, therapeutics, diagnostics and regenerative medicine is given.

Sunday - Wednesday 26–29 March 2017

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10168-1, Session 1

Multifunctional materials and tomographic methods for structural damage characterization *(Keynote Presentation)*

Kenneth J. Loh, Univ. of California, San Diego (United States)

Structural systems are susceptible to damage and, if they remain undetected, can propagate to cause catastrophic failure. Structural health monitoring (SHM) is crucial for identifying damage initiation, directing repair, and ensuring system safety/reliability. This presentation outlines a new paradigm shift in SHM, where sensors are designed from a materials perspective stemming from a "bottom-up" design methodology. In doing so, one can engineer multifunctional materials that possess a diverse suite of engineering functionalities, such as sensing of specific external stimuli (e.g., strain and pH). A few examples will be highlighted. The first case examines multifunctional nanocomposite thin films engineered with electrical properties that are sensitive to strain (for monitoring deformation, impact, and cracks) or pH (for monitoring corrosion). A scalable fabrication method based on spray-coating is proposed so that it is amenable to large-scale implementation. In addition, by coupling the films with an electrical impedance tomography (EIT) algorithm, these "sensing skins" are able to localize and characterize damage severity. Its applications for SHM of composite structures (such as wind turbine blades), metallic systems, and cement composites will be presented. However, one limitation of EIT is that it requires a set of electrodes to be permanently installed at the boundaries of the sensing skin. Thus, the second example illustrates how one can leverage a different modality of electrical excitation to interrogate structures and characterize subsurface damage without requiring pre-installed electrodes. In that regard, nanocomposites embedded in structural components then serve as passive elements that accentuate damage occurring in the system through electro-mechanical or electro-chemical means. An electrical capacitance tomography algorithm and interrogation system can map electrical property changes within the material, thereby enabling non-contact, non-invasive, surface and subsurface damage characterization. Numerical modeling and experimental results will be presented for validating this proposed SHM method.

10168-2, Session 1

Monitoring osseointegration and developing intelligent systems *(Keynote Presentation)*

Liming W. Salvino, Office of Naval Research (United States)

Effective monitoring of structural and biological systems is an extremely important research area that enables technology development for future intelligent devices, platforms, and systems. This presentation provides an overview of research efforts funded by the Office of Naval Research (ONR) to establish structural health monitoring (SHM) methodologies in the human domain. Basic science efforts are needed to utilize SHM sensing, data analysis, modeling, and algorithms to obtain the relevant physiological and biological information for human-specific health and performance conditions. This overview of current research efforts is based on the Monitoring Osseointegrated Prosthesis (MOIP) program. MOIP develops implantable and intelligent prosthetics that are directly anchored to the bone of residual limbs. Through real-time monitoring, sensing, and responding to osseointegration of bones and implants as well as interface conditions and environment, our research program aims to obtain individualized actionable information for implant failure identification, load estimation, infection mitigation and treatment, as well as healing assessment. Looking ahead to achieve ultimate goals of SHM, we seek to expand our research areas to cover monitoring human, biological and engineered systems, as well as human-machine interfaces. Examples of such include 1) brainwave monitoring and neurological control, 2) detecting and evaluating brain injuries, 3) monitoring and maximizing human-technological object teaming, and 4) closed-loop setups in which actions can be triggered automatically based on sensors, actuators, and data signatures. Finally, some ongoing and future collaborations across different disciplines for the development of knowledge automation and intelligent systems will be discussed.

10168-3, Session 2

Effect of pressure on nonlinear ultrasonic wave modulation

Suyeong Jin, Sang Eon Lee, Jung-Wuk Hong, KAIST (Korea, Republic of)

We investigate the nonlinear wave caused by interaction of fatigue cracks, and study the effect of pressure on the magnitude of nonlinear waves. Nonlinear wave modulation is generated when two ultrasonic waves having different frequencies passing through cracks, and the so-called nonlinear ultrasonic wave modulation technique is developed using this property. However, the magnitude of the nonlinear waves decreases as the contact pressure increases because the large pressure prevents the cracks from opening and closing in motion. Even if the nonlinear wave modulation occurs in the damaged structures under pressure, the magnitude would become different. Consequently, finding the range of pressure in which the nonlinear wave modulation occurs is essential to use the technique for structural components that have constraint compression. In order to examine the relations between pressure and nonlinear wave modulation, we conduct simulations under various constant pressures. The numerical model consists of two aluminum thin plates contacted to each other under constant pressure, and the contacted surfaces are modeled to be irregular mimicking the real cracks. The roughness of the crack is determined using the crack width probability density function obtained from optical measurement of fatigue cracks. In this study, we provide a proper range of contact pressure that makes the technique effective, and figure out the specific conditions in which the nonlinear wave might have large magnitudes.

10168-4, Session 2

Multimodal location algorithm for Lamb waves propagating through anisotropic materials

Abdul Rehman, Christophe A. Paget, Mark Courtier, Airbus Operations Ltd. (United Kingdom)

Composite material used in aerospace structures has grown over the last two decades and more recently there has been an increase in use of anisotropic composite layup. One of the most promising structural health monitoring techniques is Acoustic Emission (AE) using guided waves. Previous location algorithms, capable of locating damage such as cracks, delamination and debonding, have focused their application to either isotropic or quasi-isotropic structures. Some work was also dedicated to anisotropic structures based on the propagation of a single Lamb wave mode.

The scope of this work is to include different lamb wave modes that are generated by the AE to improve the location; there are cases where it is

likely that different modes have triggered different transducers for the same event. Therefore a location from a traditional unimodal algorithm will be wrong. In the frequency-thickness range of 3 Hz-m to 1800 Hz-m where there are 2 modes present, the A0 and S0 that can trigger the transducers. The two modes have different velocities and therefore produce different time of flights so they are considered separately. By adding a 4th sensor to the location algorithm and using certain mathematical and physical assumptions, the triggering mode for each sensor can be identified and the correct location found.

The final step is to give an area of the AE event location rather than a point which considers the possible errors that may occur these include the number of half periods of the first arrival missed by the sensors, this can occur if the first part of the signal is not of sufficient amplitude to trigger the sensor. Measurement errors of the time of flight difference, its velocities and sensor coordinates also contributes to further location error. The robustness of the algorithm will finally be tested by simulation adding an error to the input data.

10168-5, Session 2

Dispersion curve extraction of Lamb waves in isotropic plates by matrix pencil method

Che-Yuan Chang, National Institute of Aerospace (United States) and North Carolina State Univ. (United States); Fuh-Gwo Yuan, North Carolina State Univ. (United States) and National Institute of Aerospace (United States)

Lamb wave dispersion curves for isotropic plates are extracted from measured sensor data by matrix pencil (MP) method. A piezoelectric wafer emits a linear chirp signal as broadband excitation to generate Lamb waves in isotropic plates. The propagating waves are measured at discrete locations along a wave ray direction with a sensor 1-D laser Doppler vibrometer (LDV). The out-of-plane velocities are first Fourier transformed into either space-frequency x-ω domain or wavenumber-time k-t domain. The matrix pencil method is then employed to extract the dispersion curves for various wave modes simultaneously. In addition, the phase and group velocity dispersion curves are deduced by the relation between wavenumber and frequency. In this research, the inspections for dispersion relations on isotropic plates are demonstrated and compared by two-dimensional Fourier transform (2D-FFT) and MP method. The results are confirmed by theoretical curves computed numerically. It has demonstrated that the MP method is robust in recognizing different wave modes, including higher order ones.

10168-6, Session 2

The adhesive effect on ultrasonic Lamb wave detection sensitivity of remotely-bonded fiber Bragg grating sensors

Junghyun Wee, Drew A. Hackney, Kara J. Peters, Philip D. Bradford, North Carolina State Univ. (United States)

We previously demonstrated that the sensitivity of surface bonded fiber Bragg grating (FBG) sensors to structural ultrasonic waves can be increased by bonding the optical fiber away from the FBG location. Here, we investigate the specific mechanisms leading to this increased sensitivity for the remotely-bonded FBG which is due to the absence of adhesive on the grating, compared to FBGs that are directly bonded therefore covered with adhesive. In this work we apply the finite element (FE) method to model an optical fiber bonded to a thin aluminum plate with an adhesive. The fundamental symmetric (S0) Lamb wave was generated in the plate and coupled to the optical fiber through the adhesive, producing fundamental longitudinal (L01) and flexural (F11) traveling waves. The ideal location for the remote FBG, for measuring L01 mode without the effects of F11 mode, is right after the separation. To investigate the adhesive effect on wave detection, the FBG locations and adhesive surface were fixed, varying the adhesive modulus and thickness. We observed that decreasing the modulus reduces the signal damping effect but also produces a shear lag effect. Finally, we demonstrate that the shear lag effect induced by the adhesive causes the signal amplitude difference between the directly and remotely bonded FBGs. This study verifies that the increased detection sensitivity for the remotely-bonded FBG is due to adhesive properties, providing a beneficial reference for adhesive selection.

10168-7, Session 2

Damage identification in plate and shell structures by trilateration method using Lamb waves

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The algorithms that detect the damages and their locations play a vital role in SHM of structure under test (SUT). In recent years, PZT patches are widely appreciated in sensor network form for monitoring the health of isotropic and composite structures. In particular, the high frequency Lamb waves are generated and sensed by these patches, to diagnose the damages in SUT. A two-stage algorithm, which detects and locates damages in thin walled structures using Lamb wave signals is proposed.

Isotropic plate and shell structures with adhesively bonded PZT transducers in circular and rectangular array patterns are considered. Lamb waves are generated and sensed by these transducers in pitch-catch mode, before and after making damages in the SUT for baseline subtraction [1].

In the damage identification process, first the correlation coefficient is determined using current and baseline signals [1]. Further the Trilateration method [2] is adopted to locate the damage. Parameters like Time-of-Flight and Group velocity are estimated from the damage-scattered Lamb wave signals and used in Trilateration of all actuator-sensor pairs to localize the structural damage. The magnitude of the damage-scattered Lamb wave signals and the correlation coefficient are considered to display the damage severity in visualizing the structural damage.

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10168-135, Session 2

Synchronous separation, seaming, sealing and sterilization (S4) using brazing for sample containerization and planetary protection

Yoseph Bar-Cohen, Mircea Badescu, Xiaoqi Bao, Hyeong Jae Lee, Stewart Sherrit, David Freeman, Sergio Campos, Jet Propulsion Lab. (United States)

The potential return of samples back to Earth in a future NASA mission would require protection of our planet from the risk of bringing uncontrolled biological materials back with the samples. In order to ensure this does not happen, it would be necessary to “break the chain of contact (BTC)”, where any material reaching Earth would have to be inside a container that is sealed with extremely high confidence. Therefore, it would be necessary to

contain the acquired samples and destroy any potential biological materials that may contaminate the external surface of the container while protecting the sample itself for further analysis. A novel synchronous separation, seaming, sealing and sterilization (S4) process for sample containerization and planetary protection has been conceived and demonstrated. A prototype double wall container with inner and outer shells and Earth clean interstitial space is used for this demonstration. In potential future mission, the double wall container would be split into two halves and prepared on Earth, while the potential in orbit execution would consist of inserting the sample into one of the halves which is then mated to the other half and brazed. The use of brazing material that melts at temperatures higher than 500oC would assure sterilization of the exposed areas since all carbon bonds are broken at this temperature. The process would be executed in two-steps, Step-1: the double wall container halves would be fabricated and brazed on Earth; and Step-2: the process would be executed on-orbit. To prevent potential jamming during the process of mating the two halves of the double wall container and the extraction of the brazed inner container, a double cone-within-cone approach has been conceived. The results of this study will be described and discussed.

10168-8, Session 3

A robust signal processing method for quantitative high-cycle fatigue crack monitoring using soft elastomeric capacitor sensors

Xiangxiong Kong, Jian Li, William Collins, Caroline R. Bennett, The Univ. of Kansas (United States); Simon Laflamme, Iowa State Univ. of Science and Technology (United States)

A large-area electronics (LAE) strain sensor, termed soft elastomeric capacitor (SEC), has shown great promise in fatigue crack monitoring. The SEC is able to monitor strain changes over a mesoscale structural surface and endure large deformations without being damaged under cracking. Previous tests verified that the SEC is able to detect, localize, and monitor fatigue crack activities under low-cycle fatigue loading. In this paper, to examine the SEC's capability of monitoring high-cycle fatigue cracks, a compact specimen is tested under cyclic tension loads with varying load ranges, designed to ensure realistic crack opening sizes representative of those in real steel bridges. To overcome the difficulty of low signal amplitude and relatively high noise level under high-cycle fatigue loading, a robust signal processing method is proposed to convert the measured capacitance time history from the SEC sensor to power spectral densities (PSD) in the frequency domain, such that signal amplitude can be extracted at the dominant loading frequency. A crack damage indicator is proposed as the ratio between the square root of the amplitude of PSD and load range. Results show that the crack damage indicator offers consistent indication of crack growth.

10168-9, Session 3

On the modeling and characterization of an interlocked flexible electronic skin

Nazanin Khalili, Hani E. Naguib, Univ of Toronto (Canada)

Development of an electronic skin with ultra-high pressure sensitivity is now of critical importance due its broad range of applications in human-robot interactions such as prosthetic skins and biomimetic robotics. Microstructured conductive composite elastomers can acquire mechanical and electrical properties analogous to those of natural skin. One of the most prominent features of human skin is its tactile sensing properties which can be mimicked in an electronic skin. Herein, an electrically conductive composite comprising polydimethylsiloxane and conductive fillers is used as a flexible and stretchable piezoresistive sensor. The electrical conductivity is induced within the elastomer matrix via carbon nanotubes whereas the piezoresistivity is obtained by means of microstructuring the surface of the substrate. An interlocked array of different features in micro-scale allows the change in the contact resistance between two thin layers of the composite upon application of an external load. Deformation of the interlocked arrays endows the sensor with an ultra-high sensitivity to the external pressures within the range of human skin perception. Moreover, using finite element analysis and an analytical model, the contact resistance change of the sensor are captured for different range of pressure stimuli. The structure of the sensor can be optimized through an optimization model in order to acquire maximum sensitivity. Proper constraints are imposed and the optimal range for the designated decision variables is obtained within the defined domain of variables. The experimental results are then compared with their theoretical counterparts showing a good tracking ability of the proposed modeling methodology.

10168-10, Session 3

Carbon nanotube thin film strain sensor models from image analysis

Bo Mi Lee, Kenneth J. Loh, Univ. of California, San Diego (United States)

Carbon nanotubes (CNT) have been regarded as having high potential for fabricating next- generation thin film sensors, particularly, due to their outstanding electrical, mechanical and thermal properties. A mainstream approach to fabricate CNT-based thin film strain sensors is by dispersing and depositing them in a polymer matrix so that they form a percolated and conductive network. Numerical simulations have been employed to offer fundamental insights on the relationship between how nano-scale parameters affect the piezoresistive or strain sensing properties of the bulk film. However, many computational models make assumptions and simplifications regarding, for example, the physical properties of CNTs and polymers, which can affect modeling results. Therefore, the objective of this study is to incorporate the physical properties of CNTs (i.e., lengths and dispersed shapes of CNTs) as part of a 2D CNT-based thin film numerical model and to compare simulations of strain sensing properties with experimental results. First, multi-walled carbon nanotube (MWCNT)-Pluronic thin films were fabricated by vacuum filtration. Second, the electrical and electromechanical properties of MWCNT-Pluronic thin films (with five different concentrations) were evaluated. Third, the nano- and micro-scale physical properties of the thin films and CNTs were investigated by atomic force microscopy and image analysis. Then, the experimental measurements were used as inputs to the 2D thin film model, which was subsequently used for computing the MWCNT-based thin film model's electromechanical properties. Finally, the strain sensing properties of the numerical model were compared to those obtained from experimental tests conducting using the MWCNT-Pluronic thin films. With an experimentally validated model, the vision is that numerical modeling can help guide the design and optimization of CNT-based thin film strain sensors.

10168-11, Session 3

3D printing of highly elastic strain sensors using polyurethane/multiwall carbon nanotube composites

Josef F. Christ, Cameron J. Hohimer, Nahal Aliheidari, Amir Ameli, Changki Mo, Washington State Univ. Tri-Cities (United States)

As the desire for advanced wearable electronics increases and the soft robotics industry advances, the need for new sensing materials has also increased. Recently, there have been many attempts at producing novel materials which exhibit piezoresistive behavior. However, one of the major shortcomings in strain sensing technologies is in the fabrication of such sensors. While there is significant research and literature covering the various methods for developing piezoresistive materials, fabricating

complex sensor platforms is still a manufacturing challenge as conventional sensors are discrete, directional, and are not often integrated within the system of interest. This research aims to bridge this gap between the design and fabrication of stain sensors through the integration of fused deposition modeling (FDM) and piezoresistive nanocomposites.

In this research, pure thermoplastic polyurethane (TPU) and TPU/multiwall carbon nanotubes (MWCNT) nanocomposites were printed in tandem using a low-cost multi-material FDM printer to fabricate uniaxial and biaxial embedded strain sensor platforms with various patterns of conductive paths. The sensors were then subjected to a series of cyclic strain loads. Preliminary results showed good piezoresistive responses of the sensors with cyclic repeatability in both the axial and transverse directions. Further, while strain-softening did occur, it was predictable and similar to the results found in other literature.

10168-12, Session 3

Enhanced PVDF properties by multi-wall-carbon-nanotube (MWCNT) for efficient energy harvesting

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Piezoelectric materials such as polyvinylidene fluoride (PVDF) or lead zirconate titanate (PZT) are the fundamental materials for piezoelectric based energy harvesters. However, the drawbacks for these two materials are: (i) poor mechanical properties of PZT (e.g., brittle, low fracture stress); (ii) low energy efficiency of PVDF. It is well known that PVDF is also a kind of pyroelectric material. Extensive research has been made on investigating its piezoelectric property. But very few attentions have been paid on pyroelectric property. In this paper, we report a new design of PVDF using a very low concentration of multi-wall-carbon-nanotube (MWCNT) in PVDF to enhance both the mechanical property and piezoelectricity of PVDF. Through a series of well-controlled experiments, we found that there is a coupling effect between piezoelectricity and pyroelectricity in PVDF. Our experimental result shows that the generated electricity by PVDF/MWCNT composite with coupled piezoelectric and pyroelectric effect exceeds the arithmetic summation of individual piezoelectric and pyroelectric effects. Scanning Electron Microscope (SEM) and X-Ray diffraction (XRD) images were used to investigate the transformation of crystal structure from α phase to β phase with different concentrations of MWCNT in PVDF. Dielectric property of PVDF/MWCNT composite is also studied.

10168-13, Session 3

Multifunctional mechanoluminescent composites for self-powered sensing of vibrational loadings

Elias Pullaim, George Hoover, Dhruv Tiparti, Donghyeon Ryu, New Mexico Institute of Mining and Technology (United States)

Aerospace structures operate in harsh environmental condition with limited energy source. Damage can occur in the structural systems, and some of those can result in catastrophic structural failure unless timely detected. To prevent the catastrophes, it is crucial to detect damage in timely manner before the damage occurrence jeopardizes structural integrity. While many advanced sensor technologies have played a pivotal role in damage detection in structural health monitoring framework, those state-of-the-arts are still limited due to constant energy demand, among some others.

This study aims for devising multifunctional mechanoluminescent (ML) composites capable of autonomously detecting damage without external power supply. Unlike the current state-of-the-art sensor technology, the multifunctional ML composites do not require external energy supply. Instead, it can sense mechanical vibrations by measuring the electrical current generation autonomously produced from the composites. Here, the research objective of this study is three-fold. First, the multifunctional ML composites are designed to properly couple multiphysics phenomena of two functional materials, such as elastico-ML (EML) copper-doped zinc sulfide (ZnS:Cu) materials and poly(3-hexylthiophene) (P3HT). Under vibrational loadings, the EML ZnS:Cu-embedded elastomeric composites emit light. Then, the P3HT-based thin film, which is coated on the ZnS:Cu-embedded composites, generates electrical current. Second, EML properties of the ZnS:Cu-embedded composites are characterized under various vibrational loadings. Last, the self-powered capabilities of the ZnS:Cu/P3HT-based multifunctional composites are validated using a modal shaker.

10168-14, Session 3

Semiconductor nanomembrane based sensors for high frequency pressure measurements

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In this paper, we demonstrate improvements on semiconductor nanomembrane (NM) based high frequency pressure sensors that utilize SOI (Silicon on Insulator) NM techniques in combination with nanocomposite materials. The accurate measurement of high frequency pressure fluctuations in complex flows is critical, because current computational methods do not provide sufficiently accurate pressure results for such complex flows. Indeed, a major role for surface pressure fluctuation measurements is to provide a challenging standard for boundary layer transition studies. Transition of flow from laminar to turbulent results from amplification of instabilities and perturbations. The low-modulus, conformal nanomembrane sensor skins with integrated interconnect elements and electronic devices could be applied to vehicles or wind tunnel models for full spectrum pressure analysis.

Semiconductor nanomembrane sensors currently developed are thin, mechanically and chemically robust materials that may be patterned in two dimensions to create multi-sensor element arrays that can be embedded into small probe tips or conformally attached onto model surfaces. The sensors are thin and surface-mounted, causing minimal interaction with the flow, or potentially can be applied as an applique, and require no cavities or recesses in the test articles other than holes to connect the sensor array leads to data acquisition wiring. The material is resistant to normal fluids and solvents, can potentially operate over a temperature range, and is capable of withstanding erosion.

Experimental data presented in this paper demonstrates that: 1) silicon nanomembrane may be used as single pressure sensor transducers and elements in sensor arrays, and 2) the arrays may be instrumented to map pressure over the surfaces of test articles over a range of Reynolds numbers, temperature and other environmental conditions. Of most importance, we have 1) shown that the sensor elements are highly sensitive to both shear and normal pressure (measured minimum detectable pressure of 0.1 Pa and frequency response from DC up to 1MHz), 2) developed two types of sensor packages for the demonstration of normal pressure sensing with a miniature probe tip and shear pressure sensing with a floating element, and 3) confirmed operation in wind tunnel and shock tube tests on several test articles.

10168-500, Session Plen

Adaptive structures: a personal historical perspective

James E. Hubbard Jr., Univ. of Maryland, College Park (United States)

No Abstract Available

10168-15, Session 4

A video processing approach based on texture analysis and Bayesian decision making for autonomous crack detection in the reactor internal components of nuclear power plants

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For the safe operations of nuclear power plants, it is crucial to regularly inspect the reactor internal components. Currently, a technician manually locates the cracks on metallic surfaces from the inspection videos, which is tedious, time-consuming and subjective. Thus, an autonomous crack detection methodology is needed in this regard. The cracks on metallic surfaces are typically very tiny with low contrast, where the existing vision-based methods tend to miss-detect the cracks. Furthermore, the scratches, welds, and grind marks in the background lead to lots of false positives if state-of-the-art crack detection methods are used. As a result, a novel method is proposed based on texture recognition and Bayesian data fusion. Local Binary Pattern (LBP) is used to detect crack patches in video frames, and the crack bounding boxes are formed from these patches. In addition, the bounding boxes in different video frames are aggregated using Bayesian decision theory, which enhance the reliability and robustness of detection results. Integral histogram and a 2-stage Support Vector Machine (SVM) are applied to expedite the computation speed. A thousand of frames from several inspection videos were used to evaluate the performance of the proposed method. The results show that the proposed method is robust and efficient, while the other existing methods fail to perform well.

10168-16, Session 4

Shape management method of large structure based on Octree space partitioning using terrestrial laser scanning

Gichun Cha, Seunghee Park, Byoungjoon Yu, Sungkyunkwan Univ. (Korea, Republic of)

The objective of the study is to construct the shape management method contributing to the safety of the large structure. In Korea, the research of the shape management is lack because the new attempted technology. Terrestrial Laser Scanning(TLS) is used for measurements of large structures. TLS provides an efficient way to actively acquire accurate the point clouds of object surfaces or environments. The point clouds provide a basis for rapid modeling in the industrial automation, architecture, construction or maintenance of the civil infrastructures. TLS produce a huge amount of point clouds. Registration, Extraction and Visualization of data require the processing of a massive amount of scan data. The octree can be applied to the shape management of the large structure because the scan data is reduced in the size but, the data attributes are maintained. The octree space partitioning generates the voxel of 3D space and the voxel is recursively subdivided into eight sub-voxels. The point cloud of scan data was converted to voxel and sampled.

The experimental site is located at Sungkyunkwan University. The scanned structure is the steel-frame bridge. The used TLS is Leica ScanStation C10/C5. The scan data was condensed 92% and the octree model was constructed with 2 millimeter in resolution. This study presents octree space partitioning for handling the point clouds. The basis is created by shape management of the large structures such as double-deck tunnel, building and bridge. The research will be expected to improve the efficiency of structural health monitoring and maintenance.

10168-17, Session 4

Full-field structural dynamics by video motion manipulations

Yongchao Yang, Charles Farrar, David Mascareñas, Los Alamos National Lab. (United States)

Structures with complex geometries, material properties, and boundary conditions, exhibit spatially local, temporally transient, dynamic behaviors. High spatial and temporal resolution vibration measurements and modeling are thus required for high-fidelity characterization, analysis, and prediction of the structure's dynamic phenomena. For example, high spatial density mode shapes are needed for accurate vibration-based damage localization. Also, higher order vibration modes typically contain local structural features that are essential for high-fidelity dynamic modeling of the structure. In addition, while it is possible to build a highly-refined mathematical model (e.g., a finite element model) of the structure, it needs to be experimentally validated and updated with high-resolution vibration measurements. However, it is a significant challenge to obtain high-resolution vibration measurements using traditional techniques. For example, accelerometers and strain-gauge sensors provide low spatial resolution measurements. Laser vibrometers provide high-resolution measurements, but are expensive and make sequential measurements that are time-consuming. On the other hand, digital video cameras are relatively low-cost, agile, and provide high spatial resolution, simultaneous, measurements. A new framework will be presented for the blind extraction and visualization of the full-field, high-resolution, dynamic parameters of an operating structure from the digital video measurements using video motion manipulation and unsupervised machine learning techniques. It will be demonstrated that this high-resolution, full-field dynamic characterization framework opens up a variety of applications that traditionally have not been possible. These include the ability to accurately localize minute, non-visible, structural damage, and a new method enabling realistic video-space, high-fidelity simulations and visualizations/animations of structural dynamics.

10168-18, Session 4

Visual based laser speckle pattern recognition method for structural health monitoring

Kyeongtaek Park, Marco Torbol, Ulsan National Institute of Science and Technology (Korea, Republic of)

This study conducts the system identification of a target structure using the laser speckle pattern taken by a camera using a non-contact based method. The diffuse reflection of a laser beam generates the speckle pattern on the surface of the target object. The camera with a red filter records the scattered speckle particles of the laser light in real time. The raw speckle images of the pixel data are downloaded to the graphic processing unit (GPU). The algorithm for laser speckle contrast analysis (LASCA) computes the laser speckle contrast image and the laser speckle flow image. Virtual nodes are used as a degree of freedoms. The virtual nodes are computed by k-mean clustering algorithm that classifies pixels in each frame and each clusters' centroid from the algorithm tracks the displacements of node according to its degree of freedom. The fast Fourier transform (FFT) and the frequency domain decomposition (FDD) computes the modal properties of the structure: natural frequencies, mode shapes, and damping ratio. This

study takes advantage of a large scale computational capability of GPU. The whole algorithm used in this study is built in Compute Unifies Device Architecture (CUDA) C programming language, which enables to perform real time processing of time series speckle images.

10168-19, Session 5

Urban underground infrastructure mapping and assessment

Dryver R. Huston, Tian Xia, Dylan Burns, Taian Fan, Dan Orfeo, Yu Zhang, The Univ. of Vermont (United States)

This paper discusses research centered on a smart cities approach to the mapping and condition assessment of urban underground infrastructure. Underground utilities comprise a set of critical infrastructure for all modern cities. They carry drinking water, storm water, sewage, natural gas, electric power, telecommunications, steam, etc. In most cities, the underground infrastructure reflects the growth and history of the city with many components aging, in unknown locations with congested configurations and in unknown condition. The research approach uses sensing and information technology to determine the state of infrastructure and provide it in an appropriate, timely and secure format for the managers, planners and users. The sensors include ground penetrating radar and buried sensors. A high-speed telecommunications network collects the data. Information processing techniques convert the data in information-laden databases for use in analytics, graphical presentations, metering and planning. The databases are primarily an overlay of Building Information Modeling (BIM) and Geographical Information Systems (GIS) formats. Data will be presented from construction of the St. Paul St. CCTA Bus Station Project in Burlington, VT and utility replacement sites in Winooski, VT. The soil conditions are favorable for GPR sensing and make it possible to locate buried pipes and soil layers. The present state of the art is that the data collection and processing procedures are manual and somewhat tedious. Technical challenges and proposed for solutions for automating these procedures including high-resolution position registration and automated database population will be discussed.

10168-20, Session 5

Recent developments in disaster mitigation and sustainable engineering

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The author proposed to use novel technologies/materials such as smart structures/materials and related technologies to enable revolutionary prevention/mitigation of disasters. A typical example is the deployable breakwater which can be used daily for energy harvesting, small enough not to be an obstacle, as well as a smart breakwater autonomously deployable by the force/energy and material of tsunami or high wave. The author discussed with Furuya and Nonami on new reliable approaches to cope with disasters, which intends to enable sustainability as well as disaster mitigation, and they named it as "Disaster Mitigation and Sustainable Engineering." The author has established a research committee as a part of JSME (The Japan Society of Mechanical Engineers) M&P (Materials and Processing) division. In this paper, new ideas and developments for smart disaster mitigation toward future especially based on smart structures/materials are described. To explain the proposed concept more comprehensively, two examples, that is, artificial forest and novel deployable structure based on honeycomb to be used against flooding etc. are proposed and demonstrated. Many other smart challenges and products are also introduced and future directions are discussed. The researches listed below are mainly undergoing by the author and/or his collaborators. 1) Applications of Piezoelectric Polymers in Electrical Power Generation Using Ocean Waves (Su). 2) Dynamic Deployment of Smart Inflatable Tsunami Airbags (TABs) for Tsunami Disaster Mitigation (Shahinpoor). 3) A Novel Underwater Inflatable Structures for Smart Costal Disaster Mitigation (Adachi). 4) Structural Health Monitoring of Pipelines for Environment Pollution Mitigation (Felli et al.). 5) The Contribution of LARES to Global Climate Change Studies with Geodetic Satellites (Sindoni et al.). 6) Smart Disaster Mitigation in Italy (Felli et al). 7) Smart Disaster Mitigation in Thailand (Aimmanee et al.). The following are also undergoing. Asanuma, Kubo, Maruyama and Tanaka started to develop a multi-layered flexible and deployable structural material system to diminish the force of tsunami and dissipate its energy by separating water flow and letting them conflict with each other. Various outstanding challenges have been also done in industries and some are already commercialized. The following products are attractive, that is, neo RiSe land-mounted movable flap-gate type seawall (Hitachi Zosen), Project MOSES, Aqua Dam, and so on. In addition, Takenaka Corporation proposed innovative "Breakwater and breakwater group." Disaster Mitigation and Sustainable Engineering has to be brushed up to become a basis for the above introduced emerging field with more variety of disasters to be smartly overcome or rather utilized.

10168-21, Session 5

Recursive subspace-based identification of linear time-varying system

Jun-Da Chen, Chin-Hsiung Loh, National Taiwan Univ. (Taiwan)

In this study, comparison on several recursive update algorithms of subspace system identification are discussed for estimating dynamic characteristics of a time-varying multi-input multi-output (MIMO) system using the past-input/output multivariable output-error state space (PO-MOESP) based algorithms. First, the recursive subspace identification with Bona-fide LQ renewing algorithm (RSI-BonaFide-Oblique) incorporated with moving window technique is utilized to identify modal parameters such as natural frequency, damping ratio and mode shape at each time instant during the earthquake excitation, which assumes the equivalent linear dynamic characteristic in every moving window with a fixed length. Different from the RSI-BonaFide-Oblique algorithm the other two algorithms are based on matrix inversion lemma, which keeps the same data window with RSI-BonaFide-Oblique technique only for the initial identification, and then appends the following data points to identify modal parameters for the whole excitation time history. To identify the time-varying system a forgetting factor is then introduced in this algorithm so as to emphasize the latest state of system in these methods. Among these two matrix inversion based methods, the first one conducts oblique projection of future input-output (I/O) data matrix with instrumental variables constructed from past I/O measurements (called RSI-Inversion-Oblique), while the second one performs orthogonal projection for eliminating process and measurement noises using the same data Hankel matrix (called RSI-Inversion-Orthogonal).

In addition to identify the instantaneous dynamic characteristics of the structural system, several damage detection algorithms related to the reconstructed inter-story stiffness and flexibility matrix derived from previously identified modal parameters are also explored to quantify the damage extent, specify its corresponding damage location and the time of occurrence during the excitation. To demonstrate the capability among these three recursive subspace identification algorithms, dynamic response data from a shaking table test of a four-story steel structure is used to verify these algorithms on detecting damage caused by nonlinear behaviour on the steel column and fracture of bolt connections on a beam-column joint respectively.

10168-22, Session 5

Evaluation of truss bridges using distributed strain measurements

Kyle E. Van Der Kooi, Neil A. Hoult, Queen's Univ. (Canada)

In 2013, one in every nine steel bridges in North America was deemed to be in need of repair, retrofit or replacement. There are an estimated 200,000 steel bridges in the US alone, and an estimated $76 billion is required to return all bridges back to adequate service levels. Monitoring of structures

can provide information as to when repair should occur, which can reduce the amount of repair needed and avoid failure or collapse. As a result, monitoring is crucial to ensure the long-term longevity of these structures along with the benefits of avoiding total structure replacement. Most current monitoring techniques are unable to provide both distributed and dynamic data for structural assessments. The use of dynamic distributed fibre optics strain sensors has overcome these limitations. A scaled down steel truss bridge modeled after the Mile 17.7 bridge near Grimsby, Ontario was constructed and distributed fibre optics were installed on each member. The experimental program used short term cyclic loading to simulate the passage of a train over the bridge. The distributed strain measurements were used to determine both the axial and bending strains along the full length of each member. The results indicated that the strains distribution under the same loading conditions varied between the first and third loading cycles due to slip at the connections and that a state of self-stress was developed. The results of the study suggest that in-service steel structures immediately after construction may also be subjected to similar behaviour as a result of member and connection slip.

10168-23, Session 5

A new method for detection of fatigue cracking in steel bridge girders using self-powered wireless sensors

Hassene Hasni, Amir H. Alavi, Pengcheng Jiao, Nizar Lajnef, Michigan State Univ. (United States)

Development of fatigue cracking is affecting the structural performance of many of welded steel bridges in the United States. This paper presents a support vector machine (SVM) method for the detection of distortion-induced fatigue cracking in steel bridge girders based on the data provided by self-powered wireless sensors (SWS). The sensors have a series of memory gates that can cumulatively record the duration of the applied strain at a specific threshold level. Each sensor output has been characterized by a Gaussian cumulative density function. For the analysis, extensive finite element simulations were carried out to obtain the structural response of an existing highway steel bridge girder (I-96/M-52) in Webberville, Michigan. The damage states were defined based on the length of the crack. Initial damage indicator features were extracted from the sensor output distribution at different data acquisition nodes. Subsequently, the SVM classifier was developed to identify multiple damage states. A data fusion model was proposed to increase the classification performance. The results indicate that the models have acceptable detection performance, specifically for cracks larger than 10 mm. The best classification performance was obtained using the information from a group of sensors located near the damage zone.

10168-24, Session 6

Heating and thermal control of brazing technique to break contamination path for potential Mars sample return

Xiaoqi Bao, Mircea Badescu, Yoseph Bar-Cohen, Sergio Campos, Jet Propulsion Lab. (United States)

Potential Mars sample return is of great interest to the planetary science community as it would enable extensive analysis of samples. It is important to make sure such a mission concept would not bring any living microbes that may possibly exist on Mars back to Earth's environment. A brazing sealing and sterilizing technique was proposed to break the Mars-to-Earth contamination path. Effectively heat the brazing zone in high vacuum space and control the sample temperature for integrity are one of main challenges for the implementation of the technique. The break-the-chain procedures for proposed container configurations were simulated by multi-physics finite element models. Different heating methods including induction heating and resistance-radiation heating were evaluated. The temperature profiles of Martian samples in the proposed container were predicted. The results show that the sealing and sterilizing process can be controlled such that the samples temperature is maintained below the required level and the brazing technique is a feasible approach to break the contamination path.

10168-25, Session 6

Variable input observer-predictor for structural health monitoring of high-rate systems

Jonathan Hong, Applied Research Associates, Inc. (United States) and Iowa State Univ. College of Engineering (United States); Simon Laflamme, Liang Cao, Iowa State Univ. (United States); Jacob Dodson, Air Force Research Lab. (United States)

High-rate systems operating in the 10 μs – 10 ms timescale are likely to experience damaging effects due to the high possibility of rapid environmental changes (e.g., turbulence, ballistic impact). Some of these systems could benefit from real-time state estimation to enable their full potential. Examples of such systems include blast mitigation strategies, automotive airbag technologies, and hypersonic vehicles. Particular challenges in high-rate state estimation include: 1) complex time varying nonlinearities of system (e.g. noise, noise, uncertainty, and disturbance); 2) rapid environmental changes; 3) requirement of high convergence rate. Previously, a Variable Input Observer (VIO) was proposed by the authors as a potential solution to high-rate state estimation. The VIO is centered around the idea of a real-time adaptation of the input space by sequentially identifying the best inputs that would preserve the essential dynamics of the system under estimation. To further investigate the VIO potentials, we will not only focus on estimating the system state, but also predicting the high-rate system dynamics and possible damages. We propose a modified VIO such that it can be used as a predictor in addition to an observer, termed as Variable Input Observer-Predictor (VIOP). We demonstrate the high convergence rate of the VIOP through varying of the input space of a state estimation function.

10168-26, Session 6

Accelerated damage visualization using binary search with fixed distance laser ultrasonic scanning

Byeongjin Park, Hoon Sohn, KAIST (Korea, Republic of)

Laser ultrasonic scanning, especially full-field wave propagation imaging, is attractive for damage detection due to its noncontact nature, sensitivity to local damage, and high spatial resolution. However, its practicality is limited because scanning at a high spatial resolution demands a prohibitively long scanning time. Inspired by binary search, an accelerated laser scanning technique is developed to localize and visualize damage with reduced scanning points and scanning time. The distance between the excitation point and the sensing point during scanning is fixed in this technique to maintain a high signal-to-noise ratio for measured ultrasonic responses. First, the approximate damage boundary is identified by examining the interactions between the ultrasonic waves and damage at the sparse scanning points that are selected by the binary search algorithm. Here, a time-domain laser ultrasonic response is transformed into a spatial ultrasonic domain using a basis pursuit approach so that the interactions between the ultrasonic waves and damage, such as reflections and transmissions, can be better identified in the spatial ultrasonic domain. Then, the region inside the identified damage boundary is visualized as damage. The performance of the proposed accelerated laser scanning technique is validated through the experiment performed on an aluminum plate with a crack. The number of scanning points that is necessary for damage localization and visualization is dramatically reduced from N?M to

4log_2?N?log_2?M even for the worst case scenario. N and M represent the number of equally spaced scanning points in the x and y directions, respectively, which are required to obtain full-field wave propagation images of the target inspection region.

10168-27, Session 6

Physics-based structural health monitoring using the time-frequency analysis of electro-mechanical impedance signal

Farshad Zahedi, The Univ. of Texas at Arlington (United States)

In this paper, a self-diagnosis technique is introduced for structural health monitoring based the time-frequency analysis of electromechanical impedance (EMI) signals. It is shown that the EMI signature is essentially a pulse-echo signal represented in the frequency domain, and it can be converted into the time domain using the convolution theorem. In addition, the time-frequency plot is generated from the calculated time domain signals to cover a wide range of excitation frequency and provide a more comprehensive damage detection capability. Presenting the EMI signal in the time and the time-frequency domains provides the physical insights that explain how different factors influence the EMI signature. As such, the time domain signal acquired from the EMI is divided into "resonant phase" and "echo phase". The resonant phase includes the immediate response of the sensor to the excitation and is used to monitor the sensor bonding layer condition, while the echo phase only includes wave reflections from structural damages and is implemented for the structural damage detection. Finally, the proposed method is implemented on a beam structure to successfully detect and localize structural damage in the presence of a damage in the sensor bonding layer.

10168-28, Session 6

Strain field reconstruction on composite spars based on the identification of equivalent load conditions

Alessandro Airoldi, Lorenzo Marelli, Paolo Bettini, Giuseppe Sala, Politecnico di Milano (Italy)

Composite structures in aerospace constructions are nowadays characterized by the presence of large monolithic elements, such as spar, panes or frames, subjected to complex loads conditions. Lightweight, reliable and accurate systems can be applied to monitor the strains in these elements, based on ribbons carrying a network of optical fibres endowed with a large number of FBG sensors [1,2], Such systems can be used for the identification of real conditions, deformed configurations and of reference time-variable stain fields during the operative life of the vehicles. Moving from preliminary results [3], this work proposes a method based on the identification of a parameterized load system, which is carried out by developing a reference FE model of the component and by applying a least square method, refined with a Tikhonov regularization, to minimize the residual between the reference model and the acquired local strains. The method is virtually tested by using a surrogate model of the wing, introducing modelling discrepancies with the reference model and a considerable amount of noise to represent realistic conditions. Results indicate that the identified load system can approximate the main loads acting on the spar and can be used to accurately reconstruct, with appreciable robustness, the overall strain field, including local effects of loads, as well as the displacement and the internal forces in the spar. Finally, the positions of sensors are optimized for the best trade-off between number of sensors and accuracy in strain field reconstruction by using a multi-objective genetic optimization procedure.

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10168-29, Session 6

Inverse analysis of aerodynamic loads from strain information using structural models and neural networks

Daichi Wada, Yohei Sugimoto, Japan Aerospace Exploration Agency (Japan)

Aerodynamic loads on aircraft wings are one of the key parameters to be monitored for reliable and effective aircraft operations and management. Flight data of the aerodynamic loads would be used onboard to control the aircraft and accumulated data would be used for the condition based maintenance and the feedback for the fatigue and critical load modeling. The effective sensing techniques such as fiber optic distributed sensing have been developed and demonstrated promising capability of monitoring structural responses, i.e., strains on the surface of the aircraft wings. By using the developed techniques, load identification methods for structural health monitoring are expected to be established.

The typical inverse analysis for load identification using strains calculates the loads in a discrete form of concentrated forces, however, the distributed form of the loads is essential for the accurate and reliable estimation of the critical stress at structural parts.

In this study, we demonstrate an inverse analysis to identify the distributed loads from measured strain information. The introduced inverse analysis technique calculates aerodynamic loads not in a discrete but in a distributed manner based on a finite element model. In order to verify the technique through numerical simulations, we apply static aerodynamic loads on a flat panel model, and conduct the inverse identification of the load distributions. We take two approaches to build the inverse system between loads and strains. The first one uses structural models and the second one uses a neural network.

10168-30, Session 6

A machine learning approach for damage detection of aerospace structures using self-powered sensor data

Hadi Salehi, Saptarshi Das, Michigan State Univ. (United States); Shantanu Chakrabartty, Washington Univ. in St. Louis (United States); Subir Biswas, Rigoberto Burgueno, Michigan State Univ. (United States)

This study proposes a novel strategy for damage identification in aerospace structures. The strategy was evaluated based on the simulation of the binary data generated from self-powered wireless sensors along with a pulse switching architecture. The energy-aware pulse switching communication protocol uses single pulses instead of multi-bit packets for information delivery resulting in discrete binary data. A system employing such an energy-efficient technology requires dealing with power budgets for sensing and communication of binary data that leads to time delay constraints. This paper develops an innovative data interpretation system for damage detection based on a machine learning approach using pattern recognition (PR). A spatial-temporal conditional chain was employed as part of the machine learning approach to take into account the effect of time

delay on data interpretation. Time-delayed binary data extracted from self-powered sensors was utilized to determine damage indicator variables. The performance and accuracy of the damage detection strategy was examined and tested for the case of an aircraft stabilizer. Damage states were simulated on a finite element model by reducing stiffness in a region of the stabilizer's skin. The paper presents results in terms of recognized patterns due to the simulated damage. Based on prior work, it is expected that the proposed damage detection strategy will show satisfactory performance to identify damage in spite of high noise levels. Through the simulations, it is observed that PR can be applied as a promising machine learning algorithm for damage detection using novel self-powered wireless sensors with time-delayed binary data.

10168-103, Session PMon

Multiplexed fiber Bragg grating sensor interrogation based on a Fourier domain mode-locked laser

Jinwoo Park, Yong Seok Kwon, Myeongock Ko, Chungnam National Univ. (Korea, Republic of); Han-Cheol Ryu, Sahmyook Univ. (Korea, Republic of); Min Yong Jeon, Chungnam National Univ. (Korea, Republic of)

We demonstrate a 1550 nm band resonance Fourier-domain mode-locked (FDML) fiber laser with fiber Bragg grating (FBG) array. Using the FDML fiber laser, we successfully demonstrate real-time monitoring of dynamic FBG strain sensor interrogation for structural health monitoring. The resonance FDML fiber laser consists of six multiplexed FBGs, which are arranged in series with delay fiber lengths. It is operated by driving the fiber Fabry-Perot tunable filter (FFP-TF) with a sinusoidal waveform at a frequency corresponding to the round-trip time of the laser cavity. Each FBG forms a laser cavity independently in the FDML fiber laser. The very closely positioned two FBGs in a pair are operated simultaneously with a frequency in the FDML fiber laser. The spatial positions of the sensing pair can be distinguished from the variation of the applied frequency to the FFP-TF. One of the FBGs in the pair is used as a reference signal and the other one is fixed on the piezoelectric transducer stack to apply the dynamic strain. We successfully achieve real-time measurement of the abrupt change of the frequencies applied to the FBG without any signal processing delay. The real-time monitoring system is displayed simultaneously on the monitor for the variation of the two peaks, the modulation interval of the two peaks, and their fast Fourier transform spectrum. The frequency resolution of the dynamic variation could reach up to 1 Hz for 1 s integration time.

10168-104, Session PMon

Direct laser writing of polymer micro-ring resonator ultrasonic sensors

Heming Wei, Sridhar Krishnaswamy, Northwestern Univ. (United States)

A polymer micro-ring resonator fabricated by direct laser writing optical lithography is presented and demonstrated as a high-performance ultrasonic sensor. This optical ultrasonic sensor has a broad bandwidth and high optical quality factor at a wavelength of 780 nm which ensures high detection sensitivity. As an integrated device, the fabricated sensor is able to be directly coupled by an optical fiber. The paper reports the simulation, design, fabrication, and characterization of the device. The results demonstrate that the device works as a high-performance ultrasonic sensor.

10168-105, Session PMon

Classification of composite damage from fiber Bragg grating load monitoring signals

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This paper describes a new method for the classification and identification of damage caused by fatigue and static loading in composites, by classification of the spectral features of fibre Bragg grating (FBG) signals. In aeronautical applications of composites, beside damage detection, it is very useful to know the loading type causing the damage prior to determining the repair method or perhaps replacing the part. In this study a 6 layer glass-fibre composite ([02/902/02]) was manufactured with 8 FBG sensors positioned between these layers. After cutting the composite panel into smaller coupons, and subjecting them to tension-compression fatigue test to induce matrix cracks, and a static test to induce delamination, a database of 146 (unique) sample signals corresponding to the fatigue-loaded coupons and 280 (unique) sample signals corresponding to the statically-loaded coupons was acquired. Then for each sensor, the affected output signal and the reference signal (from healthy composite coupons) were input to the independent component analysis (ICA) tool under the intuitive assumption that the damaged sample's output signal is a linear combination of the reference signal and a signal induced by the damage. Applying wavelet transformation on each of these components with Daubechies 4 mother wavelet and 6 levels of decomposition, first and higher order statistics of each subband and their average power were calculated and considered as the feature set. These features were then fed to a support vector machine (SVM) classifier with quadratic kernel, leading to 99.3% classification accuracy for the fatigue loading induced damage class and 97.5% for the static loading induced damage class.

10168-106, Session PMon

Control of equipment isolation system using wavelet-based hybrid sliding mode control

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Critical non-structural equipment, including life-saving equipment in hospitals, circuit breakers, computers, high technology instrumentations, etc., is vulnerable to strong earthquakes, and on top of that, the failure of the vibration-sensitive equipment will cause severe economic loss. In order to protect vibration-sensitive equipment or machinery against strong earthquakes, various innovative control algorithms are developed to compensate the internal forces that to be applied. These new or improved control strategies, such as the control algorithms based on optimal control theory and sliding mode control, are also developed for structures engineering as a key element in smart structure technology. The optimal control theory, one of the most common methodologies in feedback control, finds control forces through achieving a certain optimal criterion by minimizing a cost function. For example, the linear-quadratic regulator (LQR) was the most popular control algorithm over the past three decades, and a number of modifications have been proposed to increase the efficiency of traditional LQR algorithm. However, except to the advantage of simplicity and ease of implementation, LQR are susceptible to parameter uncertainty and modeling error due to complex nature of civil structures. Different from LQR control, a robust and easy to be implemented control algorithm, sliding mode control (SMC) has also been studied. SMC is a nonlinear control methodology that forces the structural system to slide along surfaces or boundaries; hence this control algorithm is naturally robust with respect to parametric uncertainties of a structure. Early attempts at

protecting vibration-sensitive equipment were based on the use of existing control algorithms as described above. However, in recent years, researchers have tried to renew the existing control algorithms or developing a new control algorithm to adapt the complex nature of civil structures which include the control of both primary and secondary structures.

The aim of this paper is to develop a hybrid control algorithm on the control of both primary and secondary (equipment) structures simultaneously to overcome the limitations of classical feedback control through combining the advantage of LQR and SMC. To suppress vibrations with the frequency contents of strong earthquakes differing from the natural frequencies of civil structures, the hybrid control algorithms integrated with the wavelet-base vibration control algorithm is developed. The performance and robustness of hybrid control algorithms in the equipment isolation system as well as the response of primary structure are evaluated and discussed through simulation study and the large scale experimental testing (on NCREE shaking table) to demonstrate the efficiency of proposed control algorithms.

10168-107, Session PMon

A smart washer based transducer to monitor the bolt connection looseness

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Bolted connection is one of the most important and common forms for joining two or more parts/components in engineering structures. The pre-load loss of bolted connection may cause serious accidents unless it is found out in time. In this paper, a “smart-washer” (SW) transducer was proposed to detect the state of bolted connection. The “smart-washer”, which can be used as a sensor or an actuator, is fabricated by embedding the piezoceramic transducer into two flat metal rings. A specimen of bolt connected steel plates was studied using a pair of “smart-washers” (SWs). They were respectively installed on each side of the specimen. One of them was used as an actuator to generate stress wave, and the other one was used as a sensor to detect the propagated wave. Time-Reversal Method was used to reverse the response of the signal in time domain and re-emit it to the excitation point. The information about the pre-load loss of bolt joints was derived by analyzing the reconstructed signal. In addition, a normalized bolt pre-load looseness index was proposed based on the wavelet energy analysis to evaluate the pre-load looseness of a bolt connection.

10168-108, Session PMon

Metal rubber extensometers for the measurement of large strains and creep

Katherine M. Berg, Hang Ruan, Richard O. Claus, NanoSonic, Inc. (United States)

This paper describes the development and testing of Metal Rubber extensometers for the nondestructive measurement of large strains and creep in materials. Strain gages are used extensively for the characterization of displacements in materials. For the measurement of small strains, foil-type metal wire gages printed on polymer substrates are commonly used. For strains larger than several percent, however, the polymer substrate may deform plastically and not recover elastically, so foil gages may be unsuitable. For such large strains, mechanical extensometers may be attached to the material under test using clips or pins. The alternative to such extensometers that is discussed in this paper is to use low modulus piezoresistive Metal Rubber sheet materials that may be elastically strained up to several hundred percent and whose electrical resistance varies as a function of strain.

Metal Rubber is a thin free-standing sheet material that is self-assembled at the molecular level using alternating bi-layers of conductive metal nanoparticles and selected polymers. By increasing the volume percentage of metal nanoclusters in the multi-layer material, electrical conductivities as high as 10E6 S/m can be achieved. By decreasing the volume percentage of the clusters, the material may be biased instead just at the conductivity percolation threshold. Around this quiescent point, compression of the material induces a local increase in the volume density of clusters, so electrical conductivity increases, and, conversely, tension of the material causes a local decrease in the cluster volume density so conductivity decreases. In this way, the material has a piezoresistive behavior. Controlling the properties of the polymer matrix allows the material to be strained greater than several hundred percent without failure.

Such materials have been configured as single-length strips and back-and-forth serpentine patterns similar to those of foil strain gages, and used to measure extensions of the sensor material itself greater than 30%, and large strains and creep in elastomers and fabrics. Experimental results allow determination of sensor response as a function of superimposed time and temperature effects, and indicate gage factors on the order of 60. Methods for extensometer attachment to test materials and data acquisition are presented.

10168-109, Session PMon

Development of a slip sensor using separable bilayer with Ecoflex-NBR film

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In present, there are many researches for robot hand to operate it with high performance. For high performance, in particular manipulator, tactile sensors are essential. One of these sensors is a slip sensor detecting relative displacement between the manipulator and an object. Major of the slip sensors were developed using micro-vibration on surface of these. In this paper, polymer film-type slip sensor is presented by using novel working principle rather than measuring micro-vibration or vibration. The sensor is comprised of bilayer with Ecoflex and NBR(acrylonitrile butadiene rubber) films divided by dielectric. When slip occur on outer surface, bilayer also have relative displacement from each other because friction-induced vibration make a clearance between two layers. This displacement make electrode on polymer surface deformed, which enable measuring the displacement by capacitance difference. Extent of slippage can be obtained not only whether there is slip but how much slip is because the more slip occur the more electrode is deformed. CNT(carbon nanotube) was employed for electrode because it creates conductive network in polymer so that it has flexible and stretchable characteristics. Also normal and shear force can be decoupled by the working principle. There is relatively small deformation than polymer to dielectric aligned between electrodes. So normal and shear force effect hardly to capacitance change. To verify developed sensor, slip test apparatus was designed and experiments were conducted.

10168-110, Session PMon

Design and analysis of compound flexible skin based on deformable honeycomb

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In recent years, more and more studies focus on compound flexible skin structures. It is a kind of compound skin used deformable honeycomb structure to support flexible panel that has a good engineering application potential. The mechanical properties of flexible skins based on deformable honeycomb are mainly up to deformable honeycomb structures. A kind of cross-shaped flexible honeycomb with good in-plane deformability was proposed by designing the shapes and arrangement patterns of honeycomb cellular. On the other hand, considering variable camber/span/chord scheme, one kind of compound flexible skin was designed in which the cross-shaped flexible honeycomb is overlay with silicone face-sheet. Researches on the mechanical property of this new cross-shaped honeycomb were carried out aiming at the deformation demand of flexible

skin, which can homologous meet the demands of deformation and load bearing. The in-plane deformation mechanism of the honeycomb structure was analyzed by representative volume element method, which derived the equivalent elastic modulus of honeycomb structures, as well as the relationship between mechanical properties and cell shape parameters. The nonlinear mechanical characteristics of cross-shaped honeycomb were researched by simulation method. In addition, experiments were performed to validate the theoretical models, which showed the derived results accordant with the analytical formulas and excellent deformable capacity of the cross-shaped honeycomb. Finally, the structure parameters of the designed compound flexible skins were discussed and the simplified formula for engineering application was derived according to the deformation and aerodynamic load of the wing surface.

10168-111, Session PMon

Design of flexible skin based on a mixed cruciform honeycomb

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As the covering of morphing wings, flexible skin is required to provide adequate cooperation deformation, keep the smoothness of the aerodynamic configuration and bear the air load. The non-deformation direction of flexible skin is required to be restrained to keep the smoothness during morphing. This paper studies the deformation mechanisms of a cruciform honeycomb under zero Poisson's ratio constraint. The morphing capacity and in-plane modulus of the cruciform honeycomb are improved by optimizing the shape parameters of honeycomb unit. To improve the out-of-plane bending capacity, a zero Poisson's ratio mixed cruciform honeycomb is proposed by adding ribs into cruciform honeycomb, which can be used as filling material of flexible skin. The mechanical properties of the mixed honeycomb are studied by theoretical analysis and simulation. The local deformation of flexible skin under air load is also analyzed. Targeting the situation of non-uniform air load, a gradient density design scheme is referred. According to the design requirements of the variable camber trailing edge wing flexible skin, the specific design parameters and performance parameters of the skin based on the mixed honeycomb are given. The results show that the zero Poisson's ratio mixed cruciform honeycomb has a large bending rigidity itself and can have a better deformation capacity in-plane and a larger bending rigidity out-of-plane by optimizing the shape parameters. Besides, the designed skin also have advantages in driving force, deformation capacity and quality compared with conventional skin.

10168-112, Session PMon

Vibration characteristics of an ultrasonic transducer composed of inner and outer piezoelectric discs

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This paper considers an ultrasonic transducer composed of piezoelectric solid and hollow discs. The inner solid disc is a transmitter and the outer hollow disc is a receiver of ultrasound. The purpose of this work is to design a disc-shape transducer with separate transmitter and receiver which are operated at a same frequency and have a same center location. The vibration characteristics of the radial and axial motions in the axisymmetric modes were investigated theoretically and experimentally. Theoretically, the differential equations of piezoelectric motions were derived in terms of mechanical displacements and electric potential, and they were solved to produce characteristic equations providing natural frequencies and mode shapes. The theoretical analysis was complimented by the finite-element analysis, which provided three-dimensional mode shapes. Experimentally, the natural frequencies and the radial in-plane motion were measured using an impedance analyzer and an in-plane laser interferometer, respectively. The results of the theoretical analysis were compared with those of experiments, and the theoretical analysis was verified on the basis of this comparison. It appeared that the fundamental frequency of the transducer was similar to but slightly higher than that of a single disc transducer of same size. It was found that the transducer composed of inner solid and outer hollow piezoelectric discs could be designed by selecting suitable diameters of each disc.

10168-113, Session PMon

Design and initial validation of wireless system for oil monitoring base on optical sensing unit

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According to the situation of oil leakage and the development of the existing oil detection technology, a wireless monitoring system, combining with the sensor technology, optical measurement technology, and wireless technology, is designed. In this paper, the overall architecture of wireless system and wireless communication technology is introduced particularly. On hardware, the data, collected by photoelectric conversion and analog to digital conversion equipment, will be sent to the upper computer by wireless and analyzed with the signal extraction algorithm with independent research and development. Besides, the results of analysis will be also submitted timely. The experimental results show that the wireless system with the characteristics of higher precision, more real-time and more convenient installation can reflect the condition of the measuring object truly and implement the dynamic monitoring for a long time on-site, stability—thus it has a good application prospect in the oil monitoring filed.

10168-114, Session PMon

Design of wireless synchronous structural monitoring system for large bridges

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Large bridges play a significant role in the development of both the urban traffic condition and the social economy. It is of high importance to monitor the operational bridges and to assess their security from the perspective of people's life and property safety. In this paper, a wireless bridge structure monitoring system was developed and DMTS synchronization algorithm (based on the one-way synchronization mechanism of the sender) which can meet the system requirement was proposed. Then the deck vibration test of a bridge in Xiamen was carried out. The study shows that the wireless sensing system has the advantage of high accuracy, and the feature of easy operation, good instantaneity, and low overhead costs, which has a good application prospect in the field of structure monitoring and condition assessment of the bridges.

10168-115, Session PMon

Research on high-speed railway's vibration analysis checking based on intelligent mobile terminal

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Recently, the development of high-speed railway meets the requirement of society booming and it has gradually become the first choice for long-length journey. Since ensuring the safety and stable operation are of great importance to high-speed trains owing to its unique features, vibration analysis checking is one of main means to be adopted. Due to the popularization of Smartphone, in this research, a novel public-participating method to achieve high-speed railway's vibration analysis checking based on smartphone and an inspection application of high-speed railway line built in the intelligent mobile terminal were proposed. Utilizing the accelerometer, gyroscope, GPS and other high-performance sensors which were integrated in smartphone, the application can obtain multiple parameters like acceleration, angle, etc and pinpoint the location. Therefore, through analyzing the acceleration data in time domain and frequency domain using the advanced data processing method, this research study body vibration characteristics of high-speed railway under various line status, companied with a data-based intelligent evaluation method. It has been validated that the smartphone-based high-speed railway line inspection system is reliable and feasible on the high-speed railway lines. And it has more advantages, such as convenience, low cost and allowing passengers to participate in. Obviously, the research has important practical significance and broad application prospects.

10168-116, Session PMon

Research on elevator ride comfort monitoring using smartphone

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With the rapid development of high-rise buildings, the requirement of the elevator's speed is growing higher. And the vibration amplitude of elevator will also increasing with the improvement of running speed. The vibration problems of elevator have become the important factors that affect the elevator ride comfort. At the same time, the strong vibration will affect the normal work of elevator and even cause accidents. So it's necessary to study the vibration characteristics of the elevator. In recent years, smartphone has developed rapidly, with a variety of sophisticated sensors. It has the powerful data processing and transmission capacity. Therefore, smartphone can be used in the monitoring field. In this paper, the author has presented an elevator ride comfort monitoring method based on smartphone. This method using Monitoring App can monitor the acceleration and inclination information using MEMS sensors embedded in smartphone. Firstly, this Monitoring App has been designed and developed. Secondly, the running procedure of one elevator was studied. It can be divided into smooth running, braking and running phases. And each phase has its own characteristics. Then a confirmatory test for an elevator was designed and conducted to monitor the acceleration and inclination of three running modes, the three running modes are single-layer, multi-layer and full-thickness. Finally, experimental results show that the elevator ride comfort monitoring method based on smartphone is stable and reliable, and this method is very convenient and economic.

10168-117, Session PMon

Using unmanned aerial vehicle for deployment of smart wireless sensors with autonomous landing system

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The demand for efficient monitoring and control systems is always increasing in enormous applications. Traditional monitoring and control systems have been successfully implemented by using permanently installed sensors that remain in fixed locations, and wired networks. The advances in wireless communication in the last decade allow the enhancement of the performance of monitoring systems through the usage of low cost and efficient wireless networks. On the other hand, and although fixed sensors are still used in most of the existing monitoring systems, mobile wireless sensors would be preferable as they allow sensor arrays to be modular and reconfigurable. The mounting of the array of wireless sensors in their location in the mobilized wireless sensor network represent the main difficulty which has to be overcome. The recent emerging of unmanned aerial vehicle (UAV) technology in monitoring systems has opened new opportunities for mounting of mobile wireless sensor. The accuracy of UAV deployment of sensors is, however, affected by different factors such as wind speed, target size and height. The aim of the present work is to design and implement an accurate system to deploy novel smart mobile wireless sensors with autonomous landing system by using UAVs. The UAV is programmed to fly to the location at which the mobile sensor is required to be deployed. The programming can be done from scratch by using UAV that already has GPS waypoint flying capabilities. At the required location the UAV will launch the sensor package at a predetermined height (in the range of 100 meter). The sensor package is equipped with a parachute which will be opened after 2 seconds from launching the sensor package. The parachute size is designed such that the sensor landing process will take place in about 60 seconds. The sensor package will autonomously land on the required position which has a target notification. The smart sensor package contains the target tracking system which is implemented with image processing program by using python programming language. Mainly two approaches were used during the target identification system which is color based identification system which uses thresholding and contour detection technique and shape identification. The python program is running on a raspberry pi hardware module which will process the images captured by its camera and will also communicate with an Arduino microcontroller to send the navigating (controlling) commands. All the image processing tasks were performed on raspberry pi which makes the process fast and also allows to make a quick decision for the controlling mechanism. It has to be mentioned that the data obtained from the sensors during landing and after deployment are wirelessly transmitted and processes by using an Xbee module and by Arduino microcontroller. In addition to all of the above features, we believe that our carful design of the hardware and software system components allows the fulfillment of any further requirement of any user, ensures the required upgradability to have enhanced performance, and achieves the minimum system cost without scarifying accuracy.

10168-118, Session PMon

Macro-fiber composites under thermal cycles for space applications

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Macro-Fiber Composites (MFCs) are a piezoelectric material typically used in a broad range of applications, from vibration dampening to actuation to structural health monitoring. These composites are space qualified but with thermal protection. They have not been significantly tested under thermally

cyclic conditions that it would experience in Low-Earth Orbit without shielding. Research has shown that the performance of MFCs varies when the MFC undergoes a thermal cycle and seems to experience a thermal memory. Only after running many cycles does the performance seem to become repeatable. This paper will outline an autonomous experiment that will be able to run impedance measurements and actuate MFCs on a 3U CubeSat to further test their performance in a space environment. The payload will include a power source, a microcontroller, an amplifier, an impedance circuit, a transceiver, and the MFCs. The hazards electronics face in the space environment, such as outgassing, electromagnetic interference, space-induced embrittlement and thermal radiation will also be considered.

10168-119, Session PMon

Active mass damper system for high-rise buildings using neural oscillator and position controller: sinusoudally varying desired displacement of auxiliary mass intended for reduction of maximum control force

Daisuke Iba, Kyoto Institute of Technology (Japan); Junichi Hongu, Tottori Univ. (Japan); Takayuki Sasaki, Souhei Shima, Morimasa Nakamura, Ichiro Moriwaki, Kyoto Institute of Technology (Japan)

A new unique control system for active mass dampers, which consisted of a neural oscillator and position controller, has been proposed. In the system, the output of the neural oscillator synchronized with structure responses is not only used as a rhythmic command to switch the motion direction of the auxiliary mass of active mass dampers, but also used to decide the desired displacement value of the auxiliary mass. In addition, in order to drive the auxiliary mass to the desire value, a PD controller is used as the position controller. In our previous study, the desired displacement value for the auxiliary mass was decided by using a phase and amplitude map including contours. However the desired value formed by the proposed method was rectangular wave, which was different in size depending on the acceleration response of structure. Therefore, at the moment the motion direction switched, the system gives the auxiliary mass and structure enormous force and is inefficient in the control performance. In this paper, in order to reduce the maximum control force at the moment the motion direction switched and improve the control performance, a new generation method for the smooth desired displacement value is proposed. The proposed method generates sinusoidal waves, which is different in size fitting to the structure response, as desired displacement values of auxiliary mass every half cycle, can connect the generated sinusoidal waves and eliminate discontinuous change in the connection. Finally, the validity of the proposed method is evaluated through numerical simulation and experiment.

10168-120, Session PMon

Development of sensing systems printed with conductive ink on gear surfaces: manufacturing of meander line antenna by laser-sintered silver nano-particles

Daisuke Iba, Shintaro Futagawa, Takahiro Kamimoto, Morimasa Nakamura, Nanako Miura, Takashi Iizuka, Arata Masuda, Akira Sone, Ichiro Moriwaki, Kyoto Institute of Technology (Japan)

The long-term objective of this research is to develop sensor systems printed conductive ink on gear surfaces for detection of gear failure signs.

Nowadays, every machine is capable of measuring in real time the physical conditions, for instance, acceleration, deformation, temperature, etc., of the mechanism. This measured parameters can be used to modify the desired conditions for the machinery operation or to detect failure for an appropriate maintenance, performance and safety. However, some measurements of machine elements cannot be done with conventional techniques due to space limitation for measurements, geometric complexity of the elements, operation conditions, such as high rotating speed and more. Specifically, gears have the geometric complexity, and rotate at high speed in the gearbox, and hence it appears that it is difficult to measure the condition of gears. Our study attempts to create new sensors for mechanical components, which are not under the same constraint as ordinary sensors. We intend to develop a new method to print sensors on the complex gear surface by using conductive ink. However, a typical printing machine is only capable of printing in two-dimensional plane. For more complex shapes such as gear surfaces, the printing tool should be introduced onto numerically controlled multi-axis machineries.

Therefore, a three-axis laser-processing machine had been developed by combining a desktop three-axis CNC milling machine and laser module in the past. This laser machine is for sintering conductive ink, which includes silver nano-particles, sprayed and dried on surfaces of steel plates insulated by a polyimide layer. The appropriate laser sintering condition for manufacturing circuits on steel plates has been unveiled, and the sintered circuits line have been evaluated by measuring the width, cross-section and electrical properties of the lines. Our aim here is to manufacture an antenna, which is necessary for transmitting information of gear condition by wireless. Especially, this paper attempts to print a meander line antenna, which has a resonance property at 600 MHz, and evaluates the actual property by measuring.

10168-121, Session PMon

Optimal control of build height utilizing optical profilometry in cold spray deposits

Michael Birnkrant, Sergey Shishkin, Abhijit Chakraborty, United Technologies Research Ctr. (United States)

Part-to-part variability and poor part quality due to failure to maintain geometric specifications pose a challenge for adopting Additive Manufacturing (AM) as a viable manufacturing process. In recent years, In-process Monitoring and Control (InPMC) has received a lot of attention as an approach to overcome these obstacles. The ability to sense geometry of the deposited layers accurately enables effective process monitoring and control of AM application. This paper demonstrates an application of geometry sensing technique for the coating deposition Cold Spray process, where solid powders are accelerated through a nozzle and impacts with the substrate and adheres to it. It is Often time the deposited surface has shape irregularities. The goal of our work was to control the deposition height. An analytical control-oriented model is developed that expresses the resulting height of deposit as an integral function of nozzle velocity and angle. In order to obtain height information at each layer, a micro-epsilon (μ-ε) laser line scanner was used for surface profiling. This surface profile information, specifically the layer height, was then fed back to an optimal control algorithm which manipulated the nozzle speed and angle to control the layer height to a pre specified height. While the problem is heavily nonlinear, we were able to transform it into equivalent Optimal Control problem linear w.r.t. input. That enabled development of two solution methods: one is fast and approximate, while another is more accurate but still efficient.

10168-122, Session PMon

An enhanced rhombus-type compliant mechanism with large displacement and high natural frequency

Qian Liu, Mingxiang Ling, Junyi Cao, Xi'an Jiaotong Univ. (China)

Aiming to break the deadlock that one must make a compromise between

the bandwidth and travel range of a compliant mechanism, this paper propose an enhanced rhombus-type compact compliant mechanism with large displacement amplification ratio and high natural frequency. It comes true by strategy of the parallel mechanism in which multiple flexure arms are superimposed. In order to eliminate the resulting strong stress concentration, a super ellipse fillet with a shoulder is designed and verified a 30 per cent reduction of stress concentration compared with the conventional circular fillet by finite element analysis (FEA). The prototype is monolithically fabricated by wire electrical discharge machining process. FEA and experimental results show that the proposed mechanism exhibits the same displacement amplification ratio but over 20 per cent increase of natural frequency compared with the commercial rhombus-type compliant mechanism under the same geometric parameters. Furthermore, exact theoretical formulas for displacement amplification ratio and natural frequency are established and comparatively verified by FEA and experiments. Multi-objective optimization based on these insightful analytical models considering the influence of stiffness of the flexure and piezo-actuator is conducted and great discrepancy is found comparing with the common practice where only the displacement amplification ratio is used as one of the multi-objective functions.

10168-123, Session PMon

Reliability based optimization of an active vibration controller using evolutionary algorithms

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Many modern industrialized systems such as aircrafts, rotating turbines, satellite booms, etc. cannot perform accurately if uninhibited vibrations affect them. Structural health monitoring and reliability calculations is a way to handle system uncertainties. As stochastic behaviors are unavoidable characteristics of all engineering systems, it is definitely recommended to take it into the account when we are going to design or operate any high precision system. Here, in this research, we use smart materials technology for monitoring of the structural health and consequently controlling the structure in a way to keep it in a reliable performance range. Regarding the uncertainty issues and structural life considerations together with the limitations in power consumption, the current study is aimed towards the utility of SHM data for reliability analysis and its application for optimizing an AVC problem while keeping the system in a safe domain of performance. As piezoelectric patches can change the strain using an electric field and inversely can produce an electric signal as a result of structural deformation with high frequency response, we utilized them for Online optimization and reliability assessment of smart structures for a sample wing as the main objective of this research.

10168-124, Session PMon

Metal rubber sensor technology to enable in-flight icing measurement

Katherine M. Berg, Jennifer H. Lalli, Richard O. Claus, NanoSonic, Inc. (United States)

This paper describes the development and testing of Metal Rubber sensor elements for the nondestructive, normal force detection of ice accretion on aerospace structures. The unanticipated buildup of ice on aircraft engine components, wings and rotorblades is a problem for both civilian and military aircraft that must operate under all weather conditions. Ice adds mass to moving components, thus changing the equations of motion that control the operation of the system as well as increasing drag and torque requirements. To a lesser extent, ice also alters the surface geometry of leading edges, altering the air flow transition from laminar to turbulent, generating turbulence and again increasing drag.

The Metal Rubber material used in these sensor elements is a piezoresistive material that exhibits a change in electrical resistance in response to physical deformation or strain. It is produced as a free-standing sheet that is assembled at the molecular level using alternating layers of conductive metal nanoparticles and polymers. As the volume percentage of the conductive nanoparticle clusters within the material is increased from zero, the onset of electrical conduction occurs abruptly at the so-called percolation threshold. Electrical conduction in Metal Rubber occurs due to electron hopping between the clusters. If a length of the material is physically stretched, the individual clusters physically move apart so the efficiency of electron hopping decreases and electrical resistance increases. The resulting change in resistance as a function of the change in strain in the material, at a specific volume percentage of conductive clusters, can be interpreted as the transduction response of the material.

This transduction response can be optimized for the intended application by increasing sensitivity and frequency response. Affecting sensor response through modification of sensor material modulus and conductivity is discussed.

10168-125, Session PMon

Low frequency motion measurement of spacecrafts and satellites with inertial monolithic sensors

Fabrizio Barone, Gerardo Giordano, Fausto Acernese, Rocco Romano, Univ. degli Studi di Salerno (Italy)

In this paper we describe the characteristics and performances of a monolithic sensor designed for low frequency motion measurement of spacecrafts and satellites, whose mechanics is based on the UNISA Folded Pendulum. The latter, developed for ground-based applications, exhibits unique features (compactness, lightness, scalability, low resonance frequency and high quality factor), consequence of the action of the gravitational force on its inertial mass.

In this paper we introduce and discuss the general methodology used to extend the application of ground-based folded pendulums to space, also in total absence of gravity, still keeping all their peculiar features and characteristics.

10168-126, Session PMon

X-ray system to visualize multiphase high viscosity fluid flow extruded from a container

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Flow dynamics visualisation can be accomplished with a variety of complex systems depending on the nature of the fluid, conditions and hosting equipment. Often the complexity of the fluid, opacity and equipment [1] can make it very hard and expensive to characterize the flow with conventional techniques and, not rarely, the diagnostic conditions cause severe alterations leading to results that are of difficult interpretation and of questionable accuracy.

Purpose of this paper is to characterize the flow of such a challenging low temperature high viscosity fluid, constrained in a deformable container of significant diameter, using X-ray and without altering the temperature conditions that would otherwise affect the viscosity and therefore the accuracy of the flow visualization results. The application also required that the overall visualization system was of approachable cost therefore without modifying commercial X-ray equipment.

Tracking particles design requirements included maximum drag to reflect accurate fluid tracking, easy identification from the X-ray data especially

in the areas of particle path convergence. The high viscosity fluid could also not achieve homogeneous temperature distribution; therefore it was also desirable to achieve a particle geometry design that would show relative fluid temperature alterations via mechanically induced amplified deformation detectable from the X-ray analysis data. Given the restriction particle size vs. X-ray resolution, this last task is particularly challenging considering the passive nature of the tracking particles. Final requirements was that the tracking particles needed to be injected in the desired location with ease and reasonable accuracy using a dedicated injection system.

Tracking particle paths, at various stages of container collapse, were computed via software to produce vectorial maps to visualize the flow in the areas of interest especially in the centre of the container and at the wall boundaries were stagnant flow was believed to be one of the reason for undesired high retainment after complete container collapse.

[1] Heindel, Theodore J. - A Review of X-Ray Flow Visualization with App

10168-127, Session PMon

A study of irradiation side sampling flat panel detector with crystal silicon based x-ray CMOS image sensor

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In recent devices for radiography, In-direct X-ray imaging method, which use the scintillator for photon converter, is most widely spread method. In flat panel detector (FPD) based on amorphous silicon system, which use thin film transistor, it is difficult to make a small photodiode pitch under 100 um because the limitation on amorphous silicon property. In mammography and high resolution non-destructive test, the device need more small size of pixel pitch than chest radiography. In this reason, the sensor based on crystal silicon CMOS sensor, which can make under 5um pitch pixel, is fabricated. Nevertheless using crystal silicon sensor with small pixel pitch, the blurring effect during photon transfer in the scintillators, such as cesium iodide and gadolinium oxysulfate, is another limited factor for high resolution.

The conventional FPD system had structure so that scintillators and photodiodes were combined in front-and-back to the incident X-ray, respectively. An FDR D-EVO, which is structured by an irradiation side sampling (ISS) FPD based on amorphous silicon system, was presented by FUJIFILM. The ISS FPD has a scintillator in the opposite direction of an incident X-ray and has advantages in better light transfer efficiency and spatial resolution comparing with conventional FPD system.

By using both ISS structure and crystal silicon based CMOS image sensor, we can make better performance FPD that has high resolution and fast frame rate. The crystal silicon based CMOS image sensor can make the pixel pitch smaller and the ISS structure can support this small size pixel pitch without losing spatial resolution by scintillator.

We have designed and fabricated the test chip of crystal based CMOS image sensor and measured MTF, NNPS, and sensitivity of this test sensor for comparing conventional and ISS structure.

10168-128, Session PMon

A magnetostrictive phased array sensor using a nickel comb patch for Lamb wave-based damage detection

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Our previous study investigated the magnetic shape anisotropy effect on sensing performance and directional sensitivity in a Magnetostrictive Patch Transducer (MPT), using a nickel patch with uniaxial or circular comb shapes, designed for an ultrasonic Lamb wave inspection technique. The comb-shaped nickel patches were machined from a disc patch made of polycrystalline nickel. Due to the magnetic shape anisotropy feature induced by forming high-aspect-ratio fingers to the nickel disc, the sensing performance and directionality of the MPT using the comb patch were noticeably enhanced, despite of the isotropic magnetostrictive characteristics of the polycrystalline nickel itself.

This paper presents the development of a Magnetostrictive Phased Array Sensor (MPAS) using a circular comb-shaped nickel patch and its damage detection capability. 24 comb fingers were constructed to a 1-inch diameter nickel disc with a 0.02-inch thickness. A mobile magnetic circuit device containing six sensing coils and biasing magnets was prototyped and all the sensing coils were arranged in a hexagon with a radius of 1 inch. The sensing coils appear to individually have a directional sensitivity specified along the normal direction of the coil winding. The magnetic circuit device detects the magnetostrictive property change on the nickel comb patch caused by the Lamb wave propagation. By altering the orientation of the magnetic circuit device, the MPAS enables to acquire Lamb wave signals from more sensing sections within the comb patch than the preselected six sensing segments, providing a high resolution damage detection scheme for the phased array signal processing technique.

10168-129, Session PMon

Prediction error variance in Bayesian model updating: a comparative study

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In Bayesian model updating, the likelihood function is commonly formulated through stochastic embedding, in which the probability model of prediction error plays an important role and is often treated as Gaussian distribution subject to the first two moments as constraints. The selection of prediction error variances can be formulated as a model class selection problem, which automatically involves a trade-off between the average data-fit of the model class and the information it extracts from the data. Therefore, it is critical for the robustness in the updating of the structural model especially in the presence of large modeling errors. To date, three ways of prediction error variances have been seem in the literature: 1) setting constant values empirically, 2) estimating them based on the goodness-of-fit of the measured data, and 3) updating them as uncertain parameters by applying Bayes' Theorem at the model class level. In this paper, the effect of different strategies to deal with the prediction error variances on the model updating performance is investigated explicitly. A six-story shear building model with six uncertain stiffness parameters is employed as an illustrative example. Hybrid Monte Carlo is used to draw samples of the posterior probability density function of the structure model parameters as well as the uncertain prediction variances. The different levels of modeling uncertainty is modeled through three FE models, including a model without any modeling error, a model with 20% error in one stiffness parameter, and a model with 50% error in the same stiffness parameter. Bayesian updating is performed for the three FE models considering the three aforementioned treatments of the prediction error variances. The effect of number of measurements on the model updating performance is also examined in the study. The results indicate that updating the prediction error variances as uncertain parameters at the model class level produces more robust results especially when the number of measurement is small and the level of modeling error is high.

10168-130, Session PMon

Vibration measurement on composite material with embedded optical fiber based on phase-OTDR

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Fiber optic sensors for aircraft health monitoring allow evaluating new avionic materials and studying the behavior of avionic structures under harsh environmental conditions of pressure, temperature and acoustic disturbance. Distributed sensors based on optical time-domain reflectometry (OTDR) are suitable for aircraft applications due to electromagnetic interference immunity, small dimensions, low weight and flexibility. These features allow the fiber embedment into aircraft structures in a nearly non-intrusive way to sense and measure vibrations along every point along the fiber length. Measuring vibrations on avionics structures is of interest for studying material fatigue and the occurrence of undesirable phenomena like flutter. Thus, the capability of evaluating an avionic structure frequency response due to applied vibration both in ground tests and on flight allows monitoring the health of the structure, enhance the aircraft design and prevent accidents. In this work, we built a composite material board containing 2.5 m of embedded polyimide coated 125 μm diameter single-mode optical fiber. The board consists of 24 laminates of composite material superposed according to the stacking sequence: 45°/-45°/0°/90°/45°/-45°/0°/90°/45°/-45°/0°/90°/90º/0°/-45°/45°/90°/0°/-45°/45°/90°/0°/-45°/45°, where the angles are the orientation of each laminate carbon fibers. The optical sensing fiber was inserted in the material middle-layer during its fabrication. The material studied was representative of that used in aircraft wings. The built composite board was used to validated a phase-OTDR system for avionic structure monitoring that comprises ~8 ns optical pulses carved from a narrow linewidth laser source using a semiconductor optical amplifier, a 400 MHz bandwidth avalanche photodetector and a 500 MSa/s analog-to-digital converter. We applied and measured vibrations from ~ 0 to 1000 Hz on the composite board with the embedded sensing fiber with a spatial resolution of ~80 cm. The response of the system was relatively flat within the entire range of frequencies studied, as confirmed by Fourier analysis.

10168-131, Session PMon

Evaluation of a new source localization method in a simulated dispersive plate

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Source localization in a dispersive medium is a complex problem that cannot be solved with reasonable accuracy using current time difference of arrival (TDOA) techniques. A building floor is an example of a dispersive medium that is being loaded by occupant footsteps. If a more reliable localization algorithm is obtained, then it can be used to localize and track occupants in a building using floor vibration sensors. The applications of localization and tracking include applications in security (intruder detection and localization), and localization of building occupants during an emergency evacuation (eg. fire emergency). In this paper we investigate a new approach to localization using the fact that the source's generated travelling wave loses energy as it travel's away from the source's origin. We use a finite element (FE) model of a plate to simulate the plate's response due to a point force, and try to estimate the source location based on measurements taken by a randomly distributed sensor network. The sensors are assumed to be accelerometers that measure the plate's out-of-plane vibration. Simulation results show that the proposed method is accurate in localizing the source (within a 5cm radius) if the source lies inside the convex hull of the sensor location points. Outside the convex hull the localization estimates become less accurate.

10168-132, Session PMon

Inversion-based imaging using lagrange polynomial parameterization and genetic algorithm optimization

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In order to enhance and monitor the integrity, the depth information of the crack is relatively important. In this paper, we proposed an efficient technique to characterize the depth profile of crack in a conducting component. The technique employed a fast yet stable boundary element method (BEM)-based forward model with LP parameterization for shape profile approximation and GA for rapidly searching and refining the shape of the crack. The BEM is used to evaluate the impedance variation due to the crack shape which are normally solve in a traditional way that requires the meshing of the domain that demands intensively the computer time and memory for obtaining the accurate solution. In our method, we show that this can be accelerated by interaction matrix reused and vectorized calculation in domain of interest, thus the fast and reliable imaging can be achieved. Also, we introduce a novel technique which is using LP interpolation to describe the profile of crack under the domain of interested. The integrated LP interpolation reduces the number of computations by selecting appropriated data that makes the inverse problem easier and faster. Then GA optimization is used to refine the shape of crack until the impedance variation matches with the reference data . GA provides a strategy that avoid local minimum based on a restarted scheme that could certainly help to achieve faster and more reliable solution. Our technique has improved the efficiency of the inversion solver. This could lead to improve the inspection procedures, especially for the benefit of aerospace industries.

10168-133, Session PMon

Wireless sensing nodes for substructure and subsurface conditions monitoring

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A structure's deterioration or failure in many cases is caused by its substructure and subsurface conditions. A recent example was that the Delaware's I-495 Bridge over the Christina River tilted due to the failure of its pile foundations, resulting in an emergency repair project that cost nearly $43 million. And yet the substructure and subsurface conditions are often omitted from being inspected and monitored mostly because of limited access. Embedding sensors and instrumentation in a substructure would enable measuring in-situ responses and performance in real time. Traditional substructure sensors are, however, typically costly, wired with cables and often bulgy, and thus limiting them from being used in large quantities or over a wide area on a global scale. Furthermore, there are a number of geophysical methods that have been utilized for mapping subsurface conditions, e.g. Ground Penetrating Radar (GPR) and active microwave remote sensing. These methods usually lack the ability to provide real-time measurements and continuous monitoring.

There are existing wireless sensor nodes that have been used successfully for mostly superstructure monitoring, which provides real-time but discrete point measurements. The potential use of a wireless sensor node for underground or subsurface monitoring faces the outstanding challenges of signal attenuation due to the conductive soil medium. It is, however, possible to correlate the variation of signal attenuation to the change of soil properties and, in return, to sense the change of soil conditions.

The objective of this study is to explore the feasibility to develop a compact wireless sensing node that integrates both global sensing and point measurements in real time. The sensing unit consists of a radio transceiver, a circuit for interfacing with sensors, a micro-electro-mechanical system (MEMS) accelerometer, and a power source. The sensing nodes are subjected to evaluation through conducting a laboratory flume test in which the nodes are embedded in soils.

10168-134, Session PMon

The use of distributed optical fiber sensing technique for pavement subgrade performance monitoring

Wanqiu Liu, Dalian Univ of Technology (China); Shujuan Wang, Jilin Provincial Transport Scientific Research Institute (China)

The control of pavement premature damages needs the systematic understanding of the damage evolution mechanism and therefore effective pavement structure on site performance monitoring tools are needed. This paper discusses the application of a distributed optical fiber based sensor in pavement subgrade performance monitoring. The proposed sensor has been embedded on top of the subgrade layer of a test section of He-da highway in China. The sensor covering length is about 200 meters. Data have been collected four times within a freezing and thawing cycle between Nov. 2015 and May 2016. The test results have proved that the sensor has high survival rate after embedding, can detect the location of cracking and measure cracking level with relatively high accuracy, and can also detect the frost heaving and thawing effect of the subgrade layer. The field application has demonstrated the feasibility of the proposed sensor in systematic performance monitoring of pavement structure.

10168-136, Session PMon

Optical-fiber point liquid-level sensor based on light scattering

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This paper introduces a silica optical fiber (SOF) sensor for liquid-level alarm in aircraft fuel tanks, which are under high temperature and high pressure. Unlike most of the optical fiber sensors monitoring the liquid-level by capturing the reflected light or refracted light, the proposed sensor is based on light scattering. The scattering light intensity has a direct relation with the suspended sediment concentration. In the air, due to its low particle concentration (about 0.2mg/m2), almost all the light continue to propagate on its ways and little light is scattered. But in the liquid, the concentration of the suspended particles is greater than 2000mg/m2, so the scattering light intensity is higher. And the scattering light intensity in different direction and different distance is different. So, a sensing element with an oblique end-face of three groups of fibers is designed to detect the liquid-level. When light propagates along the launching SOFs and reflects off the end-face. It will get scattered by some particles. Owing to the difference of the suspended particles concentration between air and liquid, the scattering light coupling back into the launch SOFs will be different. And because of the oblique end-face, the light intensity between two launch SOFs will be different. By employing a differential structure, a point liquid-level can be indicated. And with two oblique end-faces, two point liquid-levels can be detected, which is just to meet the requirements for high-low level alarm. The experimental results confirmed the sensor with a high accuracy nearly 1mm and excellent temperature adaption which still performed well at extreme temperatures like -40 degrees C and 5 degrees C.

10168-137, Session PMon

Evaluation of trajectory shaping guidance law for the spacecraft

Zhongtao Cheng, Yongji Wang, Lei Liu, Huazhong Univ. of Science and Technology (China)

In this paper, a Trajectory Shaping Guidance Law which implies small angle approximations is proposed and evaluated. Most of the guidance work done thus far is focused on approaching the target destination consuming the least amount of energy. In some specific occasion, it may also be necessary to shape the spacecraft trajectory near the destination. This paper shows how the guidance problem can be reformulated so that a guidance law that leads to the destination with least amount of energy consuming as well as travels on the desired trajectory is developed. First the space-state equation is given, as with other guidance problems, we still desire to minimize the integral of the command acceleration squared. And then, the Schwartz inequality is used to solve the optimal problem. Finally, we rewrite the trajectory shaping guidance law using line of sight angle instead of the commanded acceleration in order to get another form of the guidance law. After deriving the guidance law, we first test it in the linear world to see if it works as anticipated. In the meantime, we would like to compare trajectory shaping guidance with proportional navigation in terms of both accuracy and acceleration requirements. And then it is of interest to test the guidance law in the two-dimensional world in which the equations of motions are nonlinear. Performance of the guidance law on a realistic is evaluated. Evaluation result shows that the proposed guidance law can effectively shape the pitching angle and precisely meet the position constraints.

10168-141, Session PMon

Disbond detection using guided wave Pzt excitation in honeycomb composite sandwich structure

Chandrakant Pol, Walchand College of Engineering Sangli (India)

A promising new in-situ Health monitoring technique is developed for Honeycomb Composite Sandwich Structures HCSS. 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 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.

10168-31, Session 7A

A probabilistic model for visual inspection of concrete shear walls

Arvin Ebrahimkhanlou, Salvatore Salamone, The Univ. of Texas at Austin (United States)

Routine and labor intensive visual inspection by experienced inspectors is the current practice for assessment of our aging concrete structures. Currently, maximum width of the surface cracks is the only quantified parameter available to the inspectors. The inspector compares this parameter with the limits stated in guidelines and based on his/her judgment on other qualitative indicators decides on the damage state of the wall. Some of these qualitative indicators are the cracking pattern, crushing severity, design specifications of the wall, and its loading history. Therefore, the current practice is highly subjective, and it is based on the inspector's expertise rather documented past experimental data. In addition, the cracks width highly depend on the residual displacement of the structure. The cracks may get closed under reversal loadings like earthquakes, and the cracks width measurements may lead into underestimation of the damage. Several attempts are made to automatically capture photos of the concrete structures and extract their visual damage indicators. Despite considerable advancement in this area, yet there are several steps to be taken toward automated decision making on the damage state of the concrete structures. In this study, the damage state is considered as a probabilistic variable that depends on multiple design and loading parameter and at the same time influences multiple mechanical and visual damage indicators. The multivariable dependencies are modeled with a probabilistic model named Bayesian Network. Given the observed visual damage indicators and the

available specification of the wall, the model probabilistically answers the inquiries regarding the damage state of the wall. The model provides the best estimate based on the available data. Therefore, not all design specifications need to be known. A database of all visually documented experimental works on concrete shear walls is collected from the literature. The model is trained on a randomly selected ninety percent portion of the database, and its performance is successfully validated on the remaining unseen portion.

10168-32, Session 7A

Performance assessment of geotechnical stabilization elements using distributed fiber optic sensing

Christoph Monsberger, Helmut Woschitz, Werner Lienhart, Technische Univ. Graz (Austria); Václav Račanský, Martin Hayden, Keller Grundbau GmbH (Austria)

In civil engineering, geotechnical structural elements like micro piles, anchors or rock nails are used to underpin heavy structures or to stabilize slopes and embankments. On large construction sites hundreds of these components may be installed to provide a suitable and safe subsurface. Geotechnical load tests are usually performed on a number of these elements to optimize their length and to proof their bearing capacity. Currently, the deformations during these investigations are mostly measured with electronic sensors at the surface. However, these measurements at the top of the component do not deliver information about the load distribution along the object.

In this paper, we report about field trials on distributed sensing of various geotechnical structural elements with lengths up to 25m using a high resolution optical backscatter reflectometer. The designed setup enables strain measurements with a very high precision of about 1μm/m every 10 millimeters or even better. Due to this high spatial resolution, more than 2500 measurement positions along a 25m long object can be realized through one single measurement. In advance to the field trials, a detailed investigation of the fiber optic system was performed in the laboratory. In addition to the results of these laboratory studies, the critical process of the fiber installation in a harsh environment is discussed and the most significant results of the tests are presented.

This paper demonstrates that such fiber optic measurement systems provide a valuable extension to classical measurement methods and can be deployed to optimize geotechnical stabilization components.

10168-33, Session 7A

Response reduction methods for base isolated buildings with collision to retaining walls

Akiko Kishida, Yuki Yamashita, Nao Nishimura, Yoichi Mukai, Hideo Fujitani, Kenzo Taga, Kobe Univ. (Japan)

This paper proposes a new damper, installed in the seismic isolation system, that can change the damping force depending on the response displacement and response speed. Excessive deformation of the isolation layer during a massive earthquake may cause the layer to collide against retaining walls if there is not sufficient clearance between the building and the retaining walls. It is imperative to reduce the response displacement in newly constructed buildings as well as in existing buildings with insufficient clearance around the isolation layers. Either passive dampers may be used to effectively restrict the response displacement of the isolation layer, or the damping force could be increased. However, these solutions increase the response acceleration during a medium to small size earthquake and lower the performance of the seismic isolation structure. The proposed damper has a loose hole at the joint. Only when the response displacement exceeds a certain level, the joint collide against the edge of the loose hole and pushes or pulls the cylinder to attenuate the earthquake force. The design is intended to simply modify the shape of the pin support of existing oil dampers and requires only slight modification of existing attenuators. We investigate the efficacy and the effects of using the proposed attenuator on the responses of the superstructure, when it receives a seismic motion that causes the isolation layer to collide with the retaining walls. An experiment using a shaking table is conducted, and the results from the test are compared with those from numerical analyses.

10168-34, Session 7A

Damage detection of structures by wavelet analysis: application to seismic response of RC/Steel frames

Wen Hsueh, Chin-Hsiung Loh, National Taiwan Univ. (Taiwan)

For damage identification to be used in a SHM system, numerous methods have been studied including methods based on modal properties (natural frequencies and mode shapes) and frequency response function (FRF). However, the methods based on modal properties may have limited capabilities for early detection of local damage due to contaminated measurements and computational error that can lead to false alarm. Besides, local damage is frequently associated with higher modes and nonlinearities. For random, non-stationary, nonlinear, and transient signals, wavelet transform (WT) has been used as a signal pattern recognition method in structural damage identification.

In this study, wavelet decomposition of dynamic data using complex continuous wavelet (CWT) establishes a time-frequency representation for modal parameter estimation and system identification. Seismic response data collected from both the reinforced concrete frame and steel frames from earthquake response is discussed. First, the accuracy of CWT for the purpose of use in analysis of nonlinear response of structure is examined. Through the decomposition of vibration responses into discrete energy distribution as a joint function of time and scale. Using the wavelet energy content of wavelet coefficients, phase and the amplitude of CWT to signal with amplitude and frequency modulated and temporal variation of stiffness so that the pulses in the response of structures to strong earthquake excitation can be identified. CWT-based damage detection method is also used to investigate the stiffness degradation in a set of a single storey reinforced concrete frame as well as a 5-story steel frame subjected to earthquake excitation in a series of shake table test. Besides, through the total energy joint density function at each measurement for the pre-damage and post-damage states, detection and localization of damage can be implemented. Finally, the adaptive wavelet filter based on Morlet wavelet is used to detect symptom from vibration signal of the steel structure with early crack damage of connection.

10168-35, Session 7A

Scaled model experiments for automated sinkhole detection using ground penetrating radar

Yun-Kyu An, Man Sung Kang, Dong Jun Lee, Sejong Univ. (Korea, Republic of)

This paper presents ground penetrating radar (GPR)-based scaled model tests for automated detection of sinkholes. Sinkhole-scattered GPR signals are often difficult to be differentiated from the signals reflected from other underground objects such as manholes, pipelines, massive rocks because the shape of sinkholes is typically irregular. Thus, the decision-making for the sinkhole identification has been fully dependent on experts' experience. To automatically extract the only sinkhole-scattered signals, a new statistical pattern recognition algorithm is proposed in this study. To validate the algorithm, the 1/6 scaled soil tank model for simulating underground sinkholes is prepared. Then, a specially designed single channel GPR system is scanned to examine the detectability of artificial sinkholes with various shapes and sizes. The experimental results demonstrate that the artificial sinkholes are successfully visualized by the proposed algorithm without false alarms.

10168-36, Session 7B

Damage detection and localization algorithm using a dense sensor network of thin film sensors

Austin R. J. Downey, Iowa State Univ. College of Engineering (United States); Filippo Ubertini, Univ. degli Studi di Perugia (Italy); Simon Laflamme, Iowa State Univ. College of Engineering (United States)

The authors have recently proposed a hybrid dense sensor network consisting of a novel, capacitive-based thin-film electronic sensor for monitoring strain on mesosurfaces and fiber Bragg grating sensors for enforcing boundary conditions on the perimeter of the monitored area. The thin-film sensor monitors local strain over a global area through transducing a change in strain into a change in capacitance. In the case of bidirectional in-plane strain, the sensor output contains the additive measurement of both principal strain components. When combined with the mature technology of fiber Bragg grating, the hybrid dense sensor network shows potential for the monitoring of mesoscale systems. In this paper, we present an algorithm for the detection, quantification, and localization of strain within a hybrid dense sensor network. The algorithm leverages the advantages of a hybrid dense sensor network for the monitoring of large scale systems. The thin film sensor is used to monitor strain over a large area while the fiber Bragg grating sensors are used to enforce the uni-directional strain along the perimeter of the hybrid dense sensor network. Orthogonal strain maps are reconstructed by assuming different bidirectional shape functions and are solved using the least squares estimator to reconstruct the planar strain maps within the hybrid dense sensor network. Error between the estimated strain maps and measured strains is extracted to derive damage detecting features, dependent on the selected shape functions. Results from numerical simulations and experimental investigations show good performance of the algorithm.

10168-37, Session 7B

Metamaterial based passive wireless temperature sensor

Yirong Lin, Hasanul Karim, Luis Chavez, Norman Love, The Univ. of Texas at El Paso (United States)

This paper presents the fabrication, modeling and testing of a metamaterial based passive wireless temperature sensor consisting of an array of closed ring resonators (CRRs) embedded in a dielectric material matrix. A mixture of 70 vol% Boron Nitride (BN) and 30 vol% Barium Titanate (BTO) is used as the dielectric matrix and copper washers are used as CRRs. Conventional powder compression is used for the sensor fabrication. The feasibility of wireless temperature sensing is demonstrated up to 200 C. The resonance frequency of the sensor decreases from 11.93 GHz at room temperature to 11.85 GHz at 200 C, providing a sensitivity of 0.462 MHz/C. The repeatability of temperature sensing tests was carried out to quantify the repeatability. The highest standard deviation observed was 0.012 GHz at 200 C.

10168-38, Session 7B

Experimental study on damage detection in a wind turbine blade using a thin film sensor array

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Damage detection in wind turbine blades is difficult due to their large surfaces and complex geometry. Additionally, economic constraints limit the viability of typical off-the-shelf monitoring solutions applied to larger scales. A solution is to deploy dedicated sensor networks fabricated from inexpensive materials and electronics. The authors have recently developed a novel large-area electronic sensor that can measure strain over very large surfaces, based on soft elastomeric capacitors (SECs). The sensing system is analogous to a biological skin, where local strain can be monitored over a global area. The utilization of a hybrid dense sensor network (HDSN) of SECs and resistive strain gauges to detect, localize, and quantify damage has been previously explored through numerical simulations. Here, we experimentally investigate the HDSN's capabilities on a wind turbine blade model. The proposed HDSN is installed inside the blade and tested in a wind tunnel to simulate an operational environment. Damages in the form of cracks and delamination are introduced into the monitored section of the blade. Results demonstrate the ability of the hybrid dense sensor network to detect, localize and quantify both types of damage.

10168-39, Session 7B

Simultaneous sensing of fluid velocity and temperature using particle tracers embedding nitrobenzofurazan functionalized thermosensitive hydrogels

Filippo Cellini, NYU Tandon School of Engineering (United States); Sean D. Peterson, Univ. of Waterloo (Canada); Maurizio Porfiri, NYU Tandon School of Engineering (United States)

Particle image velocimetry is an established experimental technique for measuring the velocity field of a moving fluid by tracking the motion of small tracer particles dispersed within the flow. This technique is finding application in different fields, ranging from the aerospace to the biomedical sector. However, current particle image velocimetry methods are limited to the measurement of flow velocity and do not allow acquisition of other parameters of interest, such as flow temperature, pressure, and chemical composition. These limitations hinder the application of this technique to more complex problems, such as fluid-structure interaction or reacting flows, where the reconstruction of scalar fields such as temperature and pressure is important to fully understand the governing physics. In this study, we propose a novel tracer particle which enables direct measurement of the velocity field in a water flow and simultaneously acts as a temperature sensor by increasing its fluorescence intensity when the local fluid temperature rises above 32°C. To enable the thermoresponsive behavior of the particles, nitrobenzofurazan functionalized thermosensitive hydrogels are incorporated within optically transparent polydimethylsiloxane microspheres. Upon reversible transition above the lower critical solution temperature, the collapse of the gel structures induces a rapid increase of the nitrobenzofurazan dye emission up to two times the original emission intensity. Emission intensity and particles motion are simultaneously recorded using a camera, enabling simultaneous measurement of velocity and temperature fields. We demonstrate the application of the tracers in the study of forced thermal convection in water around a heated cylinder.

10168-40, Session 7B

Dynamic piezoresistive response of hybrid nanocomposites

Audrey Gbaguidi, Sirish Namilae, Daewon Kim, Embry-Riddle Aeronautical Univ. (United States)

Carbon based nanomaterials, such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs), exhibit remarkable electrical and mechanical properties that offer promising structural and functional applications as fillers for polymer nanocomposites. The outstanding piezoresistive behavior of these nanocomposites makes them ideal for sensing applications. In this work, carbon nanotube sheet – epoxy nanocomposites are fabricated with the addition of graphene platelets. An improvement in both electrical conductivity and piezoresistivity is observed with the combination of CNTs and graphene platelets, indicating the formation of efficient conductive networks for strain and electrical transfer in the material. We focus our efforts on examining the sensing performances of the nanocomposites under dynamic loadings. The electrical resistivity responses of the nanocomposites are measured for a wide range of loading frequency with broadly induced strain ranges. Loading conditions from very low frequencies to relatively high frequencies are examined to study sensitivity, repeatability, and reliability of the nanocomposites as sensing means. A transverse cyclic loading test is performed on end-clamped full scale nanocomposites to study the performance under low strains at both low and high frequencies. In addition, dynamic mechanical analysis (DMA) of nanocomposite specimen is performed to characterize the sensors. Wide range of frequencies as well as strains are covered with the DMA while the electrical resistivity of the nanocomposites is simultaneously measured. The performances of the nanocomposites as strain and damage sensors as well as potential applications in aerospace structures are discussed.

10168-41, Session 8A

Design and development of a prototype platform for gait analysis

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In recent years, the field of event classification and localization in building environments using sensors has seen significant growth due to its implications for energy, security and emergency protocols. The Virginia Tech Smart Infrastructure Laboratory's highly instrumented building, Goodwin Hall (VTGH), provides a robust testbed for such work, but a reduced scale testbed could provide benefits in event isolation, individual gait characterization, noise mitigation, and accelerometer placement flexibility. This paper presents a design solution to provide these benefits through the development of an isolated platform for data collection, portable demonstrations, and the development of localization and classification algorithms. Portability and gait preservation drove the platform size and the walking surface's material leaving its isolation material to be chosen based on event isolation and noise mitigation criteria. Scaled testing was performed to select the isolating materials for the design. Three system configurations of the walking plate and the isolating materials were then evaluated to define the optimal configuration. The success of the final configuration was determined by the transmissibility of external noise sources. Insight into the complex dynamics of the isolated platform through Finite Element Modeling (FEM) was key to the platform's contribution for classification algorithms. The developed model allowed for the study of the system's response to a recorded force of two human footsteps and provided critical information for proper accelerometer placement. This paper demonstrates the capabilities of the final design to isolate external disturbances within the active data collection area while preserving gait information.

10168-42, Session 8A

Characterizing footstep-induced structural vibration using K-SVD for sparse representation

Jonathon Fagert, Mostafa Mirshekari, Hae Young Noh, Carnegie Mellon Univ. (United States)

In this paper, we introduce a method to characterize unique features of pedestrians using human footstep-induced structural vibrations. Estimating indoor pedestrian's characteristics, such as their physical attributes, identities, and gait abnormalities can enable personalized services and enhance occupant quality of life through smart structure applications. Existing methods for occupant characterization include load, radio frequency (RF) and vision-based sensing. These methods often have limitations based on their operation and deployment, such as line of sight for visual sensors and sensor density for RF and load-based sensors. Furthermore, mobile device-based approaches require user interaction. To address these limitations, we utilize footstep-induced structural vibration responses. This approach enables non-intrusive characterization of occupants using sparsely deployed sensors. Main challenges in characterizing footstep-induced structural vibrations include noisy signals, a lack of a clear relationship between the overall signal and the characteristics of interest, and the inherent co-dependency of the signal characteristics. We tackle these challenges by using the K-SVD algorithm to sparsely decompose the signal into components, each of which can correlate with the characteristics of interest. Our method is based on the assumption that the number of physical factors affecting the footstep-induced structural vibration signal is few compared to the length of the measurements. We evaluate the performance of this method in characterizing weight and shoe type from human footstep-induced structural vibration data in campus buildings.

10168-43, Session 8A

Localization and tracking of footsteps via on-floor accelerometers

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Recent years have shown prolific advancements in smart infrastructures, allowing buildings of the modern world to interact with their occupants. One of the sought-after attributes of smart buildings is the ability to provide unobtrusive, indoor tracking of people's movements. Being able to track people indoors can provide a wide range of benefits in areas like security, emergency response, and occupancy estimates, to name a few. Recent research has shown promising results in building localization on a large scale, though there is still a long way to go to realize its full potential. This research presents a passive, small scale person tracking system using accelerometers placed around the edges of a walking area. Vibration measurements, produced by footsteps while a person walks around the room, are processed and evaluated to find the walker's coordinates from a grid of possible solutions. A heuristic approach is taken to perform footstep localization, using thresholding techniques and matched filters based on a reference data set. While requiring a reference data set can make this method difficult to implement on a large scale, it may be used to provide more accurate localization abilities in smaller areas. Thresholding and matched filter properties are determined from the reference data set and extrapolated to new data for localization. Several experimental and post-processing techniques for developing reference data sets are compared and discussed in this research effort. This exploratory work seeks to examine the feasibility of the matched filter approach for walker localization in a single instrumented room.

10168-44, Session 8A

Optimal design of a magnetorheological damper for smart prosthetic knees

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In this paper, a smart prosthetic knee employing MR damper and DC motor is proposed based on the kinetics characteristics of human knee. The MR damper coupled with springs works in parallel with the DC motor. During walking, the prosthetic knee has three phases. In phase 1, the MR damper is powered off and works as a traditional damper, and mechanical energy is dissipated. The DC motor works as an actuator to input positive work to flex knee joint. During phase 2, the MR damper is powered on to provide the required torque as a clutch. The DC motor is powered off. During the process, the prosthetic knee works as a spring. In phase 3, the MR damper is powered off and works as a traditional damper again. The DC motor works as a generator to supply a controllable damping force. By controlling the motor current, the damping force is adjusted.

For smart prostheses, energy consumption and weight are two important factors. The batteries used in prostheses with high energy efficiency can be lighted and downsized. As a result, the amputees with the prostheses will feel more comfortable. The MR damper is designed to minimize energy consumption and weight. The models of the MR damper and prosthetic knee are derived. Particle swarm optimization (PSO) algorithm is used to optimize the geometric dimensions of the MR damper. The objective function consists of reciprocals of total energy consumption in one gait cycle and the damper weight. Performances of the optimized MR damper are simulated and tested by experiments.

10168-45, Session 8B

Structural analysis and aeroservoelastic response simulation of smart fin operated by piezoelectric actuators

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In order to substitute a conventional fin operated by hydraulic actuator, a smart fin equipped with piezoelectric actuator was attempted. The straight, flat unimorph actuator is included along the chordwise direction in the hollow inner space of the airfoil. A hinge which is constrained except the axial rotation is located at 1/4 of the chord line, and then the smart fin may rotate rigidly in its pitch direction. Structural behavior of the present smart fin was predicted regarding the resulting actuation of the trailing edge under specific voltage input when the aerodynamic load was applied by using commercial software program ANSYS. Analysis on its aeroservoelastic (ASE) properties was also conducted. The requirements of the control system were as follows: the smart fin must maintain the pitch angle up to 10 degrees up to the flight speed of Mach 0.6, even under disturbances like gust, and respond to the pilot input within 0.1 second. ASE closed-loop block diagram was constructed with a certain control law. Based on the closed-loop block diagram, the modal analysis, aeroelastic analysis including the unsteady aerodynamics, and application of the classic control theory to the design of control were performed. The closed-loop control system was simulated first in ZAERO, and this closed-loop ASE analysis improved the flutter speed further than open-loop system did. Using the same ASE plant, the closed-loop control system of the smart fin was also simulated in MATLAB/Simulink along with a certain PID control law. The control system allowed the time simulation of the actuation of the smart fin and the performance regarding rise time, settling time and overshoot was well matched with the requirements. In the future, the improvement of the power control law will be designed to consider the disturbance.

10168-46, Session 8B

Determination of orthotropic mechanical properties of 3D printed parts for structural health monitoring

Bastien Poissenot, Steven Anton, Austin Scheyer, Tennessee Technological Univ. (United States)

The evolution of additive manufacturing has allowed engineers to use 3D printing for many purposes. As a natural consequence of the 3D printing process, the printed object is anisotropic. As part of an ongoing project to embed piezoelectric devices in 3D-printed structures for structural health monitoring (SHM), this study aims to find the mechanical properties of the 3D-printed material and the influence of different external factors on those properties. In order to develop an orthotropic material model to be used to evaluate embedded piezoelectrics for SHM, mechanical properties will be found experimentally from additively manufactured samples created using a consumer level fused deposition modeling (FDM) printer; the Lulzbot TAZ 6. Through experimental tensile testing, nine mechanical constants including three Young's moduli, three Poisson's ratios, and three shear moduli will be found to fully describe the 3D elastic behavior of the material. Also, the influence of layer thickness and border thickness compared to the size of the sample are investigated. Different 3D-printed specimens with different raster orientations will enable us to find the optimum configuration for each test. The determination of orthotropic mechanical properties of a given 3D printed part is a necessity to enable modeling of a piezoelectric transducer embedded in a 3D-printed structure.

10168-47, Session 8B

Finite difference analysis and experimental validation of 3D photonic crystals for structural health monitoring

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In this work, we validate the behavior of 3D Photonic Crystals for Structural Health Monitoring applications. A Finite Difference Time Domain (FDTD) analysis has been performed and compared to experimental data. We demonstrate that the photonic properties of a crystal (comprised of sub-micrometric polystyrene colloidal spheres embedded in a PDMS matrix) change as a function of the axial strain applied to a rubber substrate. The change in the reflected wavelength, detected through our laboratory experiments and equivalent to a visible change in crystal color, is assumed to be caused by changes in the interplanar spacing of the polystyrene beads. This behavior is captured by our full wave 3D FDTD model. This contains different wavelengths in the visible spectrum and the wave amplitudes of the reflected and transmitted secondary beams are then computed. A change in the reflectance or transmittance is observed at every programmed step in which we vary the distance between the spheres. These investigations are an important tool to predict, study and validate our understanding of the behavior of this highly complex physical system. In this context, we have developed a versatile and robust parallelized code, able to numerically model the interaction of light with matter, by directly solving Maxwell's equations. The ability to describe the real physical behavior

of such systems, without simplifying hypotheses, is an important and fundamental capability which will aid the design and validation of innovative photonic sensors.

10168-48, Session 8B

Improved equivalent circuit modeling and simulation of magnetostrictive tuning fork gyro sensors

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In this paper a new equivalent circuit is presented which describes a prototype micro-gyro sensor. The concept takes advantage of the principles employed in vibratory gyro sensors and the ductile attributes of GalFeNOL to target high sensitivity and shock tolerance. The sensor is designed as a tuning fork structure. A GalFeNOL patch attached to the y-z surface of the drive prong causes both prongs to bending the x-z plane (about the y axis) and a patch attached to the x-z surface of the sensing prong detects Coriolis-force induced bending in the y-z plane (about the x axis). A permanent magnet is bonded on top of each prong to give bias magnetic fields. A solenoid coil surrounding the drive prong is used to produce bending in the x-z plane of both prongs. The sensing prong is surrounded by a solenoid coil with N turns in which a voltage proportional to the time rate of change of magnetic flux is induced.

The equivalent circuit enables the fast and easy modeling of a gyro sensor and an electromechanical behavioral simulation using the circuit simulator SPICE. The prongs are modeled as wave guiding bending beams which are coupled to the electromagnetic solenoid coil transducer. In contrast to known network approaches, the proposed equivalent circuit is the first tuning fork model, which takes full account of the fictitious force in a constant rotating frame of reference. The Coriolis force as well as the centrifugal force on a mass are considered.

10168-49, Session 9A

Measurements of multicore microstructured optical fibers heated up to 50 degrees Cecius

Rosalind M. Wynne, Villanova Univ. (United States)

Mircostructured optical fibers have recently been considered as platforms for microfluidic devices for boimedical and manufacturing process control applications. More specifically they contribute to the sub-discipline of optofluidics were submicroliter volumes of fluids (i.e. liquids and gases) are manipulated in the micron sized channels inside of these fibers for enhanced optical detection. A special category of these fibers contain multiple cores that allow for interferometric measurement of high temperatures up to 1000 C. At low temperatures less than 50 C, coupling conditions between neighboring cores may be affected by transient external and internal thermal changes. Measurements of the coupling characteristics for a 3-core microstructured optical fibers are presented for temperatures up to 50 C. Multicore fibers with core separations of 2.5 um and 5 um were investigated. Typical inter-core coupling is governed by the separation distance of neighboring cores and conventional waveguide conditions. However, it was observed that the coupling conditions responded to thermal changes in the optical characteristics of the solid cores. Images of the mode field distribution were acquired for a range of temperatures during a 5 s period. The intensity was determined for temperatures between 20 C and 50.9 C. Significant time-dependent intercore-coupling instabilities were present for temperatures less than 22 C. The intensity of the coupled light varied according to microchannel air-low rates of 1-2mm/s. The findings presented will be helpful in determining steady-state thermal conditions for MOFs. Real-time and high speed sensing applications may benefit from the investigation of the coupling characteristics for temperatures less than 100 C.

10168-50, Session 9A

MFL based cable damage detection and quantitative analysis

Jooyoung Park, Ju-Won Kim, Junkyeong Kim, Seunghee Park, Sungkyunkwan Univ. (Korea, Republic of)

Non-destructive testing on steel cable is in great demand to prevent safety accidents at sites where many equipment using cables are installed. In this paper, magnetic flux leakage (MFL) signals were obtained and analyzed quantitatively. First, a simulation study was performed with a real elevator cable model using a finite element analysis (FEA) program. The leakage signal from the simulation were obtained with a unit Tesla and it was compared for 3 parameters: depth of defect, width of defect and inspection velocity. Then, an experiment on same conditions was conducted to verify the results of the simulation. A post-processing of the signals obtained from both the simulation and the experiment were carried out to characterize the properties of the damage by calculating the area of the MFL curve. Throughout the results, the MFL signal was quantified and then a cable damage detection was then confirmed to be feasible. In further study, it is expected that the damage characterization of an entire specimen will be visualized as well.

10168-51, Session 9A

External loading pattern recognition of self-sensing carbon nanotube (CNT) concrete: data mining approach

Shervin Khazaeli, Concordia Univ. (Canada)

Recently, self-sensing carbon nanotube (CNT) concrete has become a promising composite material among civil engineers specially in the context of Structural Health Monitoring (SHM). Apart from the mechanical properties enhancement, due to the piezo-resistivity characteristic of CNT, the smart concrete can trace the spatial-temporal changes in elastic fields under applied external loadings such that these changes are reflected in a measurable time-varying resistance at different locations. Moreover, data-driven SHM have been of great interest due to its capability to determine structural performance without necessitating the mathematical models. In this work, a framework of data-driven models has been developed to predict the external loading patterns with the aid of induced data from the electrical resistivity changes. The framework takes the advantages of the thorough application of data mining techniques. The main focus of this manuscript is to demonstrate the efficiency of the proposed framework for predicting uniaxial cyclic loading pattern applied to CNT concrete samples. To this end, by virtue of using proper data mining techniques the relationship between the loading and electrical resistivity variations is obtained and validated based on training-testing scheme and available analytical approaches. Afterwards, specific Machine Learning (ML) model is deployed to predict the behavior of the external loading. Results show that using piezo-resistivity of CNT is a valuable alternate to understand applied external loadings via an internal multifunctional smart system. In addition, as the proposed framework benefits from the data-based approach, it can be developed for online pattern recognition by means of cloud services.

10168-52, Session 9A

A novel spectral profile multiplexed FBG sensor network with application to the quasi-static and low velocity test of a Mylar sheet

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In this study we develop a novel spectral profile division multiplexed fiber Bragg grating (FBG) sensor network. The unique spectral profile of each sensor in the network is identified as a distinct feature to be interrogated. Thus, spectrum overlap is allowed during working conditions, and a specific wavelength window is not needed to be allocated to each sensor as in a wavelength division multiplexed (WDM) network. When the sensors are serially connected in the network, the spectrum output is expressed through a truncated series. To track the wavelength shift of each sensor, the problem is transformed to a nonlinear optimization, which is then solved by a modified dynamic multi-swarm particle swarm optimizer (DMS-PSO). To demonstrate the application of the developed network, a network consisting of multiple FBGs was integrated into a circular Mylar sheet which was loaded under quasi-static and low velocity impact test conditions. Using the new spectral profile division multiplexed network, more data collection points are permitted within a limited light source bandwidth. In-plane strain data was calculated from the FBG output and converted to out-of-plane deformation using a mathematical model. The calculated deformation was compared to the measured deformation determined using digital image correlation (DIC). The data processing rate of the interrogation method achieves 1Hz, allowing it to reveal the dynamic response of the Mylar sheet.

10168-53, Session 9A

Subsurface structural sensing using non-contact tomography and embedded nanocomposites

Kenneth J. Loh, Univ. of California, San Diego (United States)

Structural systems are susceptible to different types of damage, and many of them initiate and propagate from within the material. This attribute makes damage detection by visual inspection inherently challenging, and methods that could identify the severity and location of subsurface damage features are needed. This study is focused on the development of a non-contact, non-destructive evaluation method that can detect sub-surface structural damage while providing quantitative information on damage severity and its location. The technique is centered around the theory of electrical capacitance tomography (ECT). In short, an array of non-contact electrodes is arranged in a circular fashion. Electrical field excitations are propagated between electrodes to interrogate the sensing area, while the corresponding electrical response at the remaining electrodes are measured. The recorded datasets are then used as inputs for solving the ECT inverse problem in which the permittivity of the sensing region can be reconstructed. To demonstrate the validity of this technique for non-contact, subsurface damage detection, the ECT forward and inverse problems were implemented in MATLAB. A set of numerical simulations were conducted for evaluating the sensitivity of ECT for detecting material permittivity changes. Upon validation of the algorithm, experimental studies were conducted by selecting a test structure. Strain- and pH-sensitive nanocomposites (whose electrical permittivity would vary according to applied external stimuli) were spray-coated in certain regions within the test structure so that the films were beneath the surface and embedded. Laboratory tests were conducted to inflict damage to the test structures, both by applying deformation (i.e., to induce strain and damage within the material) and by subjecting the structure to different pH environments (i.e., to simulate corrosion damage). A set of non-contact electrodes were fabricated to form a ring structure, and the system was used for interrogating the test structure. The raw data was used as inputs to the ECT algorithm, in which the spatial permittivity distribution of the sensing area (i.e., the cross-section of the test structure) could be estimated. The results showed that non-contact tomography coupled with stimuli-sensitive nanocomposites could be used for non-contact, non-invasive, subsurface structural sensing and damage detection.

10168-54, Session 9A

Fiber gratings strain sensor systems for composites and adhesive joints

Ingrid Scheel, Eric Udd, Columbia Gorge Research LLC (United States)

This paper will focus primarily on the use of multidimensional strain and shear measurements drawing on prior and new work by Columbia Gorge Research to move this field of endeavor forward.

10168-55, Session 9A

Feasibility of magnetic fiber-optic based corrosion sensor

Safieh Almahmoud, Oleg Shiryayev, Nader Vahdati, Paul Rostron, The Petroleum Institute (United Arab Emirates)

A fiber optic based sensor utilizing the magnetic interaction force is proposed. The sensor aims to detect corrosion in structures, which are made from ferromagnetic materials (e.g. pipelines made of carbon steel). It consists of a beam that is made from a non-corrosive material with embedded Fiber Bragg Grating (FBG) sensor and a permanent magnet. The beam is placed in a position such that the magnetic coating is within a few millimeters away from the ferromagnetic material to allow for the generation of the magnetostatic attraction force between the sensor and the pipe. The corrosion causes a reduction in material thickness, which increases the distance between the material and the magnet, thus the attraction force will decrease. This change in the force can be related directly to the change in the strain measured by the optical fiber as it causes a shift in the wavelength of the reflected light. We present initial analytical investigation of the feasibility of the proposed concept.

10168-56, Session 9A

Optical sensing of metal tiny particles using ceria nanoparticles via fluorescence quenching technique

Nader Shehata, Effat Samir, Soha Gaballah, Mohamed Rizk, Bassem Mokhtar, Mohamed Azab, Alexandria Univ. (Egypt)

The presented work introduces a new application of synthesized ceria nanoparticles as colloidal sensors for different types of tiny particles sensing with fluorescence quenching technique. Our synthesized ceria nanoparticles are characterized to prove its capacity of O-vacancies which could be the probes for tiny particles ions such as lead (Pb) and iron (Fe). Ceria nanoparticles have reduced visible fluorescence emission peaks with increasing the metallic tiny particles concentrations under 430nm optical excitation. Stern-Volmer constants are calculated to determine ceria nanoparticles sensitivities towards the metallic tiny particles, found to be 1.6450, and 0.7681 M-1 for ceria NPs towards Pb, and Fe tiny particles respectively. This work could be helpful further in some industrial and environmental applications such as water quality or pollution monitoring.

10168-57, Session 9B

Distributed fiber optic temperature sensors and data-enhanced modeling of steel beams in fire

Yi Bao, Genda Chen, Missouri Univ. of Science and Technology (United States)

This presentation deals with high temperature measurements using a Brillouin scattering based fiber optic sensor and thermo-mechanical analysis of simply-supported steel beams subjected to a combined thermal and mechanical loading. The temperature distribution measured from the sensor is compared locally with thermocouple measurements with less than 4.7% average difference at 95% confidence level. The simulated strains and deflections are validated using measurements from a second distributed fiber optic (strain) sensor and two linear potentiometers, respectively. The results demonstrate that the temperature-dependent material properties specified in the four investigated building codes lead to strain predictions with less than 13% average error at 95% confidence level, and that the EN1993-1-2 building code provided the best predictions. However, the implicit consideration of creep in the EN1993-1-2 is insufficient when the beam temperature exceeds 800°C.

10168-58, Session 9B

Shape sensing of inflatable aerospace structures with fiber optic curvature rosettes

Justin M. Bond, Dryver R. Huston, The Univ. of Vermont (United States)

The use of inflatable structures in aerospace applications is becoming increasingly widespread. In order to monitor the inflation status and overall health of these inflatables, an accurate means of shape sensing is required. Efforts have been made to measure simple curvature using embedded Fiber-Bragg Gratings. An established method utilizes a pair of FBGs separated by a known distance. Dividing the difference in strain by the separation distance yields an experimental value for the one-dimensional curvature at a point. We fabricated a curvature-sensing FBG pair on an inflatable membrane and tested its accuracy as the membrane was shaped into a known radius of curvature. This work reports on the assembly of three such curvature-sensing FBG pairs into a two-dimensional curvature-sensing rosette. The goal is to use this rosette to measure the curvature of a surface in multiple directions at a single point. A 3-D printed surface with saddle geometry was used to calibrate the curvature-sensing rosette. Presented will be methods of extracting values for the curvature tensor for the surface at a point using the curvature-sensing rosette, along with experimental verification. This essentially defines the local geometry about the rosette, measured in real time. By employing an array of such rosettes across the surface of an inflatable structure, the local curvature of the inflatable could be known at every point. Combining these curvature measurements can yield an accurate depiction of the global geometry. Thus, the inflation status of the inflatable space structure could be monitored in real time.

10168-59, Session 9B

Test of FBG sensors for monitoring high pressure pipes

Antonio Paolozzi, Sapienza Univ. di Roma (Italy); Claudio Paris, Museo Storico della Fisica e Ctr. Studi e Ricerche “Enrico Fermi” (Italy) and Sapienza Univ. di Roma (Italy); Cristian Vendittozzi, Univ. de Brasilia (Brazil); Marialuisa Mongelli, ENEA (Italy); Hiroshi Asanuma, Chiba Univ. (Japan)

Fibre Bragg Grating (FBG) sensors are increasingly being used on a wide range of civil, industrial and aerospace structures. The sensors are created inside optical fibres (usually standard telecommunication fibres); the optical fibres technology allows to install the sensors on structures working in harsh environments, since the materials are almost insensitive to corrosion, the monitoring system can be positioned far away from the sensors without sensible signal losses, and there is no risk of electric discharge. FBG sensors can be used to create strain gages, thermometers or accelerometers, depending on the coating on the grating, on the way the grating is fixed to the structure, and on the presence of an specifically designed interface that can act as a transducer. This paper describes a test of several different FBG sensors to monitor an high pressure pipe that feeds the hydraulic actuators of a 6 degrees-of-freedom shaking table at the ENEA Casaccia research centre. On the pipe have been glued a bare FBG sensor and a copper coated FBG sensor. A third sensor has been mounted on a special interface to amplify the vibration; this last sensor can be placed on the steel pipe by a magnetic mounting system, that also allows the its removal. All the sensor are placed parallel to the axis of the paper. The analysis of the data recorded when the shaking table is operated will allow to determine which kind of sensor is best suited for structural monitoring of high pressure pipelines.

10168-60, Session 9B

Corrosion detection for steel with soft coating using in-line fiber Bragg grating sensor

Fodan Deng, Ying Huang, Fardad Azarmi, North Dakota State Univ. (United States)

Coatings generally are used to slow down the corrosion process in structural steel, but cannot fully prevent them from happening in practical. An inline corrosion monitoring system for steel based on fiber Bragg grating sensors (FBGs) was extended to steel with soft coating in this paper. Experimental results showed that as corrosion continued to happen, an increase in central wavelength of FBGs had been detected. A positive relationship between the severity of corrosion and the increase in central wavelength was also observed. This study revealed the potential of FBGs to serve as corrosion assessment technique in practical.

10168-61, Session 9B

Distributed fiber optic strain sensing to detect artificial pitting corrosion in stirrups

Jiachen Zhang, Neil A. Hoult, Queen’s Univ. (Canada); Vinutha Kancharla, National Institute of Technology (India)

Pitting corrosion is difficult to identify through visual inspection and can lead to sudden structural failures. As such, an experimental study was undertaken to investigate whether distributed fiber optic strain sensors are capable of detecting the locations and strain changes associated with stirrup corrosion in reinforced concrete beams. In comparison to conventional strain gauges, this type of sensor can measure the strain response along the entire length of the fiber optic cable. Two specimens were tested: a control and a deteriorated beam. The deteriorated beam was artificially corroded by reducing the cross sectional area of the closed stirrups by 50 percent on both sides of the stirrup at the mid height. This level of area reduction represents severe pitting corrosion. The beams were instrumented with both polyimide and nylon fiber optic sensors to measure the distributed strains, and then tested to failure under three point bending. The load deflection behavior of the two specimens is compared to assess the impact of the artificial pitting corrosion on the flexural capacity. Digital Image Correlation is used to locate the extent and trajectory of the crack paths. The strain variation data for the stirrup is examined to determine whether the artificial pitting corrosion could be detected using this data.

10168-62, Session 9B

A buoyancy-based fiber Bragg grating tilt sensor

Muneesh Maheshwari, Yaowen Yang, Nanyang Technological Univ. (Singapore)

In this paper, a novel design of fiber Bragg grating tilt sensor is proposed. This tilt sensor exhibits high angle sensitivity and resolution. The presented tilt sensor works on the principle of the force of buoyancy of a liquid. It has many advantages over the other designs of tilt sensors which have been proposed recently. The temperature effect can be easily compensated by using an un-bonded or free FBG. In this paper, the mathematics is established which shows that the Bragg wavelength (λB) varies linearly with the angle of inclination. This linear variation of Bragg wavelength with the angle of inclination is also confirmed by the experimental results. Further, the experimental and simulation results are compared and found in good agreement with each other.

10168-63, Session 9B

Embedded fiber Bragg grating sensor for the simultaneous measurement of strain and temperature

Abhay K. Singh, Haiying Huang, The Univ. of Texas at Arlington (United States); Yupeng Zhu, Ming Han, Univ. of Nebraska-Lincoln (United States)

Fiber Bragg Grating (FBGs) sensors have become a crucial topic of research in structural health monitoring, primarily due to its light weight compact size, low cost, multiplexing capability, immunity to electro-magnetic interference etc. Despite its salient features, FBG sensors suffer from the problem of cross sensitivity to strain and temperature. In the past, researchers have made a lot of efforts to address this issue through different techniques but their research was limited to the use of a single parameter, i.e. the central Bragg wavelength. Since the Bragg wavelength is sensitive to both the temperature and axial strain, a single parameter cannot differentiate the effects of strain and temperature simultaneously. In our research, we have introduced bandwidth as a parameter in addition to the central Bragg wavelength by encapsulating FBG in composite laminates. Combining the Bragg wavelength and the bandwidth enables us to decouple the combined effects of temperature and strain. Sensor fabrication, thermal-mechanical testing, and the related data processing algorithm will be discussed.

10168-64, Session 9B

Effect of gauge length on embedded fiber Bragg grating sensor response in woven fiber composites

Claire E. Davis, Andrew Philips, Patrick Norman, Nik Rajic, Defence Science and Technology Group (Australia)

Conventional non-destructive inspection approaches can be costly to implement, require physical access to the subject and some of the more established inspection methods are not effective on polymer composite materials. This has driven a growing interest in the use of embedded sensors. The physical form of optical fibres means they are well suited to embedment in fibre reinforced composites however there are technical challenges associated with their use.

The non-uniform geometry of woven fabric composite materials can induce localised macro bending in embedded optical fibre Bragg grating (FBG) sensors when they are compacted between layers during the lay-up process. This leads to a non-uniform strain profile along the optical fibres which can limit the efficacy of conventional peak tracking algorithms for demodulating strain.

This paper investigates the effect of gauge length on sensor response for FBGs of different length embedded through the thickness of a woven glass fibre reinforced composite coupon. The experimentally measured FBG reflection spectra were compared to model predictions for the unloaded state assuming an FBG bend radius of similar dimensions to the weft of the fabric. Through thickness fibre optic strains under four point loading conditions were compared with finite element model predictions and side-imaged thermoelastic response measurements. The results show that the ratio of the gauge length to the curvature radius of the macro bending is critical with the optimal gauge length being a compromise between FBG reflectivity and sensor response.

10168-65, Session 10A

The Federal Highway Administration (FHWA) Long-Term Bridge Performance (LTBP) program products: from field SHM and NDT/NDE testing to well-established data driven deterioration models

Hooman Parvardeh, Saeed Babanajad, Yun Bai, Rutgers, The State Univ. of New Jersey (United States); Robert Zobel, Federal Highway Administration Turner Fairbank Highway Research Ctr. (United States); David Masceri, Franklin Moon, Ali Maher, Rutgers, The State Univ. of New Jersey (United States)

One in nine of the nation's bridges, approximately 69,000 bridges, are rated as structurally deficient, highlighting the necessity of serious actions. To address this issue, the Long-Term Bridge Performance (LTBP) Program has been initiated since 2008 by U.S. Federal Highway Administration (FHWA) and authorized by the U.S. Congress. The LTBP program is a 20-year research effort to collect scientific performance field data from a representative sample of bridges nationwide that will help the bridge community better understands bridge deterioration and performance. Bold in its vision and unprecedented in its scope, the LTBP Program promises to move bridge engineering practice from its subjective and qualitative roots to a more objective, mechanistic, and quantitative footing. In this paper, the tangible products from this program are presented thoroughly. The key multifaceted products include LTBP Bridge Portal (an intelligent web-based platform), RABIT (an automated bridge deck assessment robot implementing five advanced NDT tests), BWIM (Bridge Weigh in Motion), and deterioration forecasting models. Further, different case study scenarios implemented by each individual product are discussed to evaluate their effectiveness in resolving the current technical issues of bridge infrastructures. The implications of these products in a number of US bridges yielded promising findings about the comparable performance of bridges throughout the nation. The results include a collection of data-driven predictive and forecasting models, and performance-based engineering tools ultimately aiming to enhance the capabilities of bridge community for optimizing their management of bridge inventories.

10168-66, Session 10A

Utilization of wireless structural health monitoring systems as decision making tools for a risk assessment of a network of railroad bridges

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There is a need to quantitatively assess the condition of railroad bridges in a rail network exposed to multi-hazards for risk assessment. Towards this end, monitoring techniques are being developed to enhance the assessment of rail bridges. Data obtained from structural health monitoring (SHM) can be used in a data-to-decision (D2D) framework in order to better maintain a structure. The more frequently that highly reliable, accurate, and relevant monitoring data are collected, the more effective the D2D framework. In this study, a permanent wireless monitoring system was designed, validated, and installed on a hundred-year-old long-span railroad truss bridge that crosses the Mississippi River near Memphis, Tennessee. This bridge is exposed to multiple hazards: seismic, scour, vehicle/barge impact, and aging. This paper describes the monitoring system and the analysis of monitoring data to assess the bridge condition and to assess the risk profile of the bridge. The paper describes the analytical framework for condition assessment including reliability and risk analysis of bridge components and for the global bridge.

10168-67, Session 10A

In-pavement fiber Bragg grating sensors for high-speed weigh-in-motion measurements

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Flexible pavement actually experiences dynamic load rather than static load which is still used in pavement design guide, such as equivalent single axle loads (ESAL) which is used by the American Association of State Highway and Transportation Officials (AASHTO) pavement design guide. Recently, a new design guides have been developed using axle load spectra to represent the vehicle loads in pavement design, such as the Mechanistic Empirical Pavement Design Guide (MEPDG). Hence, the dynamic load from the vehicles have become important to be estimated. In this study a three-dimension glass fiber-reinforced polymer packaged fiber Bragg grating sensor (3D GFRP-FBG) is introduced for in-pavement weigh-in-motion (WIM) measurement at high vehicle passing speed. Sensitivity study shows that the developed sensor is very sensitive to the installation depth and the properties of the host material. Also, the sensor showed abilities to detect different configurations of the wheel tires. The developed sensor can be applied for WIM measurement at high speed to provide better understanding for the loads that the flexible pavement has experienced and to replace stationary weight scale.

10168-68, Session 10A

Investigating extreme event loading on coastal bridges using wireless sensor technology

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Coastal infrastructure, such as highway bridges, are susceptible to many forms of coastal hazards: particularly hurricane surge and wave loading. These two forms of loading can cause catastrophic damage to aging highway infrastructure. Notable examples include the Escambia Bay Bridge – destroyed in 2004 by Hurricane Ivan – and the Biloxi Bay Bridge – destroyed in 2005 by Hurricane Katrina. It is estimated that storm damage costs the United States about $50 Billion per year. In light of this, it is crucial that we understand the damaging forces placed on infrastructure during storm events so that we can develop safer and more resilient coastal structures.

This paper presents the ongoing research to enable the efficient collection of extreme event loads acting on both the substructure and superstructure of low clearance, simple span, reinforced concrete bridges. Bridges of this type were commonly constructed during the 1950's and 60's and are particularly susceptible to deck unseating caused by hurricane surge and wave loading.

The sensing technology used to capture this data must be ruggedized to survive in an extremely challenging environment, be designed to allow for redundancy in the event of sensors or other network pieces being lost in the storm, and be relatively low cost. The prototype system described in this paper includes Wi-Fi wireless technology, rapid data transmission, and self-contained power sources such as batteries and solar panels. While this specific application focuses on hurricane hazards, the framework can be extended to include other natural hazards.

10168-69, Session 10A

Smart photonic coating for civil engineering field: for a future inspection technology on concrete bridge

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Photonic crystals have a potential application as smart materials to imaging damage of infrastructures. There are reported that design and fabrication of mechanochromic photonic crystals as strain sensor (in Proc. SPIE 9435) and a novel visualization technique of strain deformation of metal plates smart photonic coating (in Proc. SPIE 8345). In our previous report, aluminum plates were coated with opal photonic crystal film with tunable structural color. The photonic crystal films consist of a silicone elastomer that contains an array of submicron polystyrene colloidal particles. When the aluminum sheets were stretched, the change in the spacing of the colloidal particles in the opal film alters the color of the film. This approach is useful and easy to visualize mechanical deformation.

Now we will apply this technique to civil engineering field; crack detection on concrete infrastructures. We have been developing a high quality opal photonic crystal film on black color Polyethylene terephthalate, PET sheet with A3 size. The opal film sheet was cut and adhered to concreate or mortar test pieces. The adhesion between sheet and test piece by epoxy resin. The structural color of the opal sheet was changed when the crack was formed. The color changed was observed by naked eyes or portable CCD camera on site. In addition, we measured with reflection spectrum.

10168-70, Session 10A

Simultaneous identification method of damage and vehicle parameters on bridges utilizing long-gauge strain influence line under moving vehicle loads

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Currently, there have been plenty of researches conducted for two main problems in structural health monitoring, damage and vehicle parameter identification on bridges. However, only a handful of methods could achieve these two functions synchronously, which would cause the redundancy of sensors and the rise of cost in monitoring system. In this paper, a method to identify damage and vehicle parameters, such as axle load, wheelbase and velocity on a bridge simultaneously was proposed, based on the influence line of long-gauge strain. Then the influence line of long-gauge strain was derived primarily according to conventional strain influence line theory, on the basis of which the relationships among the local element bending stiffness of bridge, vehicle parameters and long-gauge strain were figured

out. The two order difference of long-gauge strain was chosen as the key index to found this identification method. Finally, to verify the reliability of this method, a set of numerical simulations were conducted, whose results showed that this method exhibited good performance.

10168-71, Session 10B

Compact piezoelectric resonance mass balance for sample verification and mass quantification

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There is a need for sample verification and mass quantification of rock, soil or ice samples obtained by sample acquisition mechanisms on landers or probes on extraterrestrial bodies. For many instruments information about the mass of the sample would aid in the interpretation of the data as well as aiding the portioning system so as not to overload instrument ports. Additionally, on a potential sample return mission it is likely that a sample confirmation or mass determination requirement would be implemented before the spacecraft would be commanded to return to Earth or Lunar orbit.

In an effort to meet these potential requirements a piezoelectric resonance balance is being developed to produce a frequency change proportional to the mass change. In previous work [Sherrit et al. 2010] we developed a resonance balance which produced large non-linear frequency changes due to the addition of large mass. In this study we have looked at a variety of resonator geometries in an effort to linearize the frequency shift with mass. In addition, we have investigated the use of oscillator/counter circuitry to track the frequency shift of the piezoelectric mass balance. In this design the frequency shifts automatically when a mass is placed on the balance and the counter circuit calculates the frequency shift. This frequency is then converted to a mass using calibration tables determined previously. The talk will focus on the design requirements and how they are effected by the local gravity and acoustic properties of the sample. Designs which allow for easy loading and unloading of the balance will be presented.

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10168-72, Session 10B

Energy harvesting from acoustic fields for self-powered sensors in pumped fluid systems

Kenneth A. Cunefare, Ellen A. Skow, Alper Erturk, Georgia Institute of Technology (United States)

Energy harvesting from an acoustic field is challenging given the low energy density available in most acoustic phenomena. A notable exception is in the domain of pumped, pressurized fluids, where acoustic pressure amplitudes may be on the order of 5~10% of the mean static pressure, in some applications reaching mega-pascal amplitudes, corresponding to acoustic intensities advantageous for energy harvesting. However, the static pressures that are common within pressurized systems require mechanically robustness for pressure containment, which prevents the use of common energy harvester configurations. Nonetheless, energy densities may be high enough such that non-resonant configurations are feasible; and, the fact that the acoustic pressure within pumped systems typically has a relatively narrow band spectrum means that power conditioning circuits may be optimized for power conversion. With power available from the pumped fluid itself, through what is termed a Hydraulic Pressure Energy Harvester, it then becomes possible to implement self-powered wireless sensing nodes. This paper describes a proof-of-concept HPEH implementation and demonstration of self-powered wireless sensors for use in a hydraulic power application.

10168-73, Session 10B

Elastically suspended backpack energy harvester with nonlinear design to enhance efficiency and comfortability

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In the last ten years, a lot of researchers have begun to look into obtaining electricity from the relative movement between humans and their backpacks that occurs during walking. Many of them strive for harvesting more energy while impact the human walking less. In this paper, an elastically-suspended backpack energy harvester featured with double-sided hard stoppers spring and a mechanical motion rectifier (MMR) is proposed, numerically simulated, and experimentally tested. The numerical simulation is to verify the enhanced energy efficiency and human comfort by the design. A shaker testing experiment is conducted to validate the numerical simulation. Compared with linear spring and non-MMR energy harvester, the new design can harvest more energy with the same walking conditions. Experiment setup will be assembled and tested to validate the simulation. Both the numerical simulation and test results show that, the nonlinearity can help reduce the stroke of the backpack movement, which results in less metabolic cost and a more comfortable user experience.

10168-74, Session 10B

The effects of damage accumulation in optimizing a piezoelectric energy harvester configuration

Eric J. Kjolsing, ANATECH Corp. (United States); Michael Todd, Univ. of California, San Diego (United States)

Bimorph piezoelectric elements are often used to harvest energy for low-power structural health monitoring systems. When these piezoelectric elements are deployed for extended periods of time and operate under near-resonant conditions, the resulting high amplitude cycling can lead to degradation of the piezoelectric element, resulting in a shift in the fundamental frequency. For scenarios in which the piezoelectric harvester is subject to slowly-varying time-dependant frequency inputs, the natural frequency shift due to degradation may cause the piezoelectric harvester to detune from resonance, subsequently affecting the harvester's power output. The current study seeks to understand how the accumulation of damage shifts the optimal tip mass and resistive load in a bimorph piezoelectric energy harvester. A cantilever piezoelectric element is modeled utilizing coupled electromechanical equations in a distributed system. The piezoelectric is subject to ground accelerations; the resulting power output is recorded for a range of tip masses and resistive loads. A rainflow analysis is then performed to calculate the piezoelectric elements tip displacement amplitude and the corresponding cycle count. A damage accumulation model based on a weighted form of Miner's rule is then used to degrade the harvester's flexural rigidity, piezoelectric capacitance, and piezoelectric strain constant. The piezoelectric is again loaded and the process repeated. The resulting power output contours reveal how the optimal realization of tip mass and resistive load changes as damage accumulates in the piezoelectric element. Apparent trends in the power output contours are explained.

10168-100, Session 10B

Effectiveness of compressed sensing and transmission in wireless sensor networks for structural health monitoring

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In Structural Health Monitoring (SHM) using seismic acceleration, Wireless Sensor Networks (WSN) is a promising tool for low-cost monitoring. Compressed sensing and transmission schemes have been drawing attention to achieve effective data collection in WSN. Especially, SHM systems installing massive nodes of WSN require efficient data transmission due to restricted communications capacity. The dominant frequency band of seismic acceleration is occupied in 100 Hz or less. In addition, the response mode on upper floors of structures is activated at natural frequency, resulting in induced vibration at a specified narrow band. Focusing attention on the vibration characteristics of structures, we introduced data compression techniques for seismic acceleration monitoring in order to reduce the amount of data. We examined a compressed transmission method by band pass filtering in Fourier transform for actual seismic acceleration. In computer simulation, we first execute Fourier transform and band path filtering to compress data. Assuming the compressed data is transmitted through computer networks, the data is uncompressed and inverse Fourier transform is performed in the receiver. In this paper, we evaluate an average error of the compressed transmission data to the original seismic acceleration. The results show the average error was 0.11 or less, in conditions where the acceleration measured on the first floor was compressed into 1/32, whereas the average error on the 4th floor reduced to about 0.02.

10168-75, Session 11A

Impedance-based structural health monitoring of additive manufactured structures with embedded piezoelectric wafer

Austin Scheyer, Steven Anton, Tennessee Technological Univ. (United States)

Embedding sensors within Additive Manufactured (AM) structures gives the opportunity to develop smart structures that are capable of monitoring the mechanical health of a system. The main limitation for AM technology is the ability to verify the geometric and material properties of fabricated structures. Over the past several years the impedance-based technique for Structural Health Monitoring (SHM) has been proven to be an effective method for sensing damage in structurers. The general principle is to excite a piezoelectric device, usually lead zirconate titanate (PZT), and measure the corresponding electrical impedance. AM provides an opportunity to embed sensors within the structure during the manufacturing process. Fused deposition modeling (FDM) was used to print the specimen for this feasibility experiment. The specimen were thin beams printed from polylactic acid (PLA) with an embedded monolithic piezoelectric ceramic disc. The impedance measurements were taken using a HP 4194-A impedance analyzer with the specimen in a free condition. Damage was simulated in the specimen by drilling holes and cutting. Part validation and SHM of components has be accomplished with embedded piezoelectric sensors. A model was derived in order to compare the experimental results.

10168-76, Session 11A

Damage imaging of an isotropic plate using matching pursuit algorithm

Ho-Wuk Kim, Fuh-Gwo Yuan, North Carolina State Univ. (United States)

A matching pursuit (MP) algorithm is an effective tool to decompose the overlapped wave packets in a signal so that each wave mode can be identified. For the successful separations of the wave packets, a proper atom function should be designed, that can well resemble the physical features of the signal of interest. In this paper, a novel atom function for the MP algorithm is proposed based on the wave propagating model due to an excitation of a Hann-windowed toneburst signal, which performs very accurately compared to the MP algorithm with the existing Gaussian-type atom functions. The decomposed wave packets, including the directly scattered wave from damage as well as the reverberant waves from the free edges of the plate, via the MP method are employed in the damage imaging algorithm. The inclusion of the reverberant waves highlights the damaged location with higher intensity than the conventional algorithm utilizing only a direct reflected wave. The proposed approach is verified from the experiment where four piezoelectric wafers can accurately identify the damage location in a plate.

10168-77, Session 11A

Ultrasonic array investigation of titanium rod integrated in bone

Jerome P. Lynch, Wentao Wang, Univ of Michigan (United States)

This paper presents the guided waves generation, sensing and detection in titanium rods integrated within a host bone. An array of actuators is employed to launch guided waves for structural health monitoring of the titanium rod structure. Another sensor array is used to receive reflected wave signals. By controlling the signals launched by the array of piezoelectric wafers, a special wave mode is enhanced for the better detection and characterization of the contact interface between the titanium rod and the bone material. Both the simulation and experimental tests of are studied in this paper. Several configurations with different depths in the bone are investigated and compared with simulation. Finally, a method based on wave energy loss is developed for verifying and determining the depth and firmness of the Titanium rod in the bone. All the results demonstrate the great potential of proposed method, which provides an accurate and effective way for the detection of stability of the prosthetics.

10168-78, Session 11A

Sensor network performance and reliability evaluation algorithms

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In general, any fault diagnosis and prognosis system, the sensor data and sensing strategy determine the accuracy to provide the timely diagnosis. Hence the reliability of sensors and its network is important. Sensor data validation is a key module in fault diagnosis system. Therefore, a pattern recognition based algorithm is proposed to validate an arbitrarily distributed sensor network and its data.

As a case, adhesively bonded Lead Zirconate Titanate (PZT) Transducers are chosen and their debonding [1,2,3] is examined through high-frequency Lamb waves. Aircraft qualified aluminium plates having a thickness of 1.5

mm are considered with surface bonded PZT patches for experimental study. Specified pattern of debondings are simulated in the sensors during fabrication. Subsequently through thickness holes are also made, to introduce structural damage in the plates.

Lamb waves are generated and sensor signals are collected before making holes in the plates to extract feature vectors. Further, the experiment is repeated with structural damage. The extracted feature vectors are employed in the pattern recognition system [4] to distinctively identify the sensor debonding, even in the presence of structural damage. In feature space, the perfectly bonded transducers form a single cluster despite the presence of structural damages; whereas the debonded transducers form multiple clusters, according to their type. The advantage of the proposed algorithm is that, it uses single frequency response data and simplified signal processing techniques like standard deviation, autocorrelation which avoids complex data processing techniques.

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10168-138, Session 11A

Optical air-coupled NDT system with ultra-broad frequency bandwidth

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We present a novel, optical ultrasound airborne acoustic testing setup exhibiting a frequency bandwidth of 1MHz in air. The sound waves are detected by a miniaturized Fabry-Pérot interferometer (2mm cavity), via the change of the optical index of refraction. Since this laser-based sensor does not contain mechanically deformable elements such as membranes or piezo crystals, it is free from mechanical resonances and has a linear frequency response expanding from the audible range (sub kHz) to the very high ultrasound (1MHz).

In order to generate such broadband signals, we have pursued two approaches: the first option is a thermoacoustic emitter, consisting of a metallized glass substrate, driven by a high-voltage impulse that rapidly heats up the air in contact with the conducting surface. The resulting acoustic signal has the shape of a Dirac pulse without any post-pulse oscillations, at considerably high amplitudes of more than 165 dB rel. 20 μPa in air. The second option is a laser-induced excitation of the test specimen. The thermoacoustic shockwave induced by a focused 100mJ laser impulse is an effective means to generate a short (and hence broadband) acoustic impulse without the need to physically contact the test specimen via immersion liquid.

We present characterization measurements and C-scans of a selected set of samples, including Carbon fiber reinforced polymer (CFRP). The high detector sensitivity allows for an increased penetration depth. The high frequency and the small transducer dimensions lead to a compelling image resolution.

10168-79, Session 11B

Development of smart wave mitigation structure using array of poles

Hiroshi Asanuma, Chiba Univ. (Japan)

This paper describes reduction of water flow velocity by array of poles as a new wave mitigation structure. This structure is based on tsunami mitigation coastal forest. As natural forests have many problems such as low fraction of trees, low visibility of ocean waves, low strength, long of time to grow, and so on. To cope with these problems, a new wave mitigation structure has been developed, which are intended to add better capability of high wave or tsunami mitigation effect to actual ones by optimizing various parameters such as configuration, distribution density and material properties. In this study, the effect of type of material and its combination were mainly investigated. According to the results, reduction rate of the flow velocity increases with increasing number of rows for each material up to a certain level, and that of poles having lower Young's modulus is generally higher than that of those having higher Young's modulus. The effect of combination of materials was also investigated and drastic increase of mitigation effect was found when soft and hard poles were combined.

10168-80, Session 11B

Adaptive vibration control of structures under earthquakes

Jiann-Shiun Lew, Tennessee State Univ. (United States); Jer-Nan Juang, National Cheng Kung University (Taiwan); Chin-Hsiung Loh, National Taiwan Univ. (Taiwan)

The paper presents a real-time system identification and control process, based on generalized predictive control techniques, for structural vibration suppression under earthquakes. In recent years, considerable effort has been devoted to the research and development of structural control techniques for the alleviation of seismic and wind response of buildings and bridges. Passive and active control strategies have been developed to protect structures from natural hazards and to improve the comfort of the occupants of the building. However, there has been little development of adaptive building control with the integration of real-time system identification and control design.

Model-based predictive control approaches have attracted much attention due to their relatively simple time-domain formulation and good performance. Among these methods, generalized predictive control (GPC), which combines the process of real-time system identification and the process of predictive control design, has received widespread acceptance and has been successfully applied to various test-beds. This paper presents a formulation of the GPC scheme for adaptive vibration control of structures under earthquakes. We will develop methodologies based on the proposed GPC technique and give a thorough investigation of the application of the proposed technique to adaptive building control with real-time system identification and control implementation. Comprehensive simulation will be performed to demonstrate and validate the proposed adaptive control technique for structures under earthquakes.

10168-81, Session 11B

A new self-powered electromagnetic damper for structural vibration control

Maziar Jamshidi, Hong Kong Univ. of Science and Technology (Hong Kong, China) and Sharif Univ. of Technology (Iran, Islamic Republic of); Chih Chen Chang, Hong Kong Univ. of Science and Technology (Hong Kong, China)

This paper presents a new self-powered hybrid electromagnetic damper that can mitigate vibration of a structure. The damper is able to switch between a power-regenerative passive mode and a semi-active mode depending on the power demand and capacity. The energy harvested in the passive mode due to suppression of vibration is employed to power up the monitoring (e.g. sensors) and electronic components (e.g. processor) necessary for the semi-active control. This provides a hybrid control capability that is autonomous in terms of its power requirement. The device mechanism and the circuitry that can realize this self-powered electromagnetic damper are described in this paper. The parameters that determine the device feasible force region are distinguished. Numerically the function of this proposed damper is evaluated by incorporated it for vibration reduction in stay cables and TMDs under external disturbances like wind and earthquake. It is demonstrated that for larger level of excitation, the damper is inclined to operate more in the semi-active mode as more power flows into the device. However motor saturation force may compensate the capability of semi-active control to further improve the performance compared to optimal passive case. Thus it is shown that an optimal range of vibration exists that within that the hybrid control has the highest performance enhancement.

10168-82, Session 11B

Integrated cable vibration control system using wireless sensors

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As the number of long-span bridges is increasing worldwide, maintaining their structural integrity and safety become an important issue. Because the stay cable is a critical member in most long-span bridges and vulnerable to wind-induced vibrations, strategies for vibration mitigation have been of interest both in academia and practice. While active and semi-active control schemes are known to be quite effective in vibration reduction compared to the passive control, requirements for equipment including data acquisition, control devices, and power supply prevent a widespread adoption in real-world applications. This study develops an integrated system for vibration control of stay-cables using wireless sensors implementing a semi-active control. Arduino, a low-cost single board system, is employed with a MEMS digital accelerometer and Zigbee wireless communication module to build the wireless sensor. The magneto-rheological (MR) damper is selected as a damping device, controlled by an optimal control algorithm implemented on the Arduino sensing system. The developed integrated system is tested in a laboratory environment using a cable to identify the effectiveness of the proposed system on vibration reduction. The proposed system is shown to reduce the vibration of stay-cables with low operating power effectively.

10168-83, Session 11B

Characteristics of spaceborne cooler vibration isolator using a pseudoelastic shape memory alloy

Seong-Cheol Kwon, Su-Eun Jang, Hyun-Ung Oh, Chosun Univ. (Korea, Republic of)

Spaceborne cooler generates an undesirable micro-vibration during its on-orbit operation and this may seriously affect the image quality of high resolution observation satellites. For the aim of assuring the high quality image of the observation satellite, most of studies have dealt with on-orbit micro-vibration isolation system with a low stiffness, but have not taken launch vibration environments into account. Hence, holding-and-release mechanisms should be considered for guaranteeing the structural safety of the cooler supported by a low stiffness isolator and isolator itself during harsh launch loads. However, this approach has increased the system complexity and lowered its reliability, in addition to increasing the total mass of the system. To overcome this drawback, in this study, a blade type passive vibration isolator employing the characteristics of a pseudoelastic shape memory alloy (SMA) was proposed. This isolator can guarantee structural safety of the cooler and the isolator itself under harsh launch vibration loads without requiring holding-and-release mechanism, while effectively isolating the cooler-induced micro-vibration. The basic characteristics of the isolator were evaluated through a dynamic loading tests and its simple equivalent model was proposed. Based on the measured characteristics and equivalent model, the effectiveness of the isolator design under launch and on-orbit environments was investigated. Furthermore, the validity of the isolator design in isolating the cooler-induced micro-vibration was evaluated through micro-vibration measurement tests.

10168-84, Session 12A

Operational modal analysis of a steel-frame, low-rise building with L-shaped construction

Rodrigo Sarlo, Pablo A. Tarazaga, Mary E. Kasarda, Virginia Polytechnic Institute and State Univ. (United States)

The Virginia Tech Smart Infrastructure Laboratory (VTSIL) uses a fully integrated, high density (728 ft2/sensor) accelerometer network to extract and track the modal parameters of Goodwin Hall, a classroom and laboratory building built in 2014. The process will be incorporated into an automated and long-term Structural Health Monitoring (SHM) method. One of the biggest disadvantages of modal parameter based SHM is its sensitivity to environmental conditions, mainly temperature, so the acceleration data acquisition is complemented by internal thermostat data as well as data from local weather stations. The low-rise, L-shaped construction and high mass, high stiffness properties of Goodwin Hall (which has a full limestone veneer) create additional challenges to modal identification in comparison to typical cases in literature, which feature mostly bridges and high-rise buildings with rectangular architectures. These structures are generally low stiffness and have geometries that are easier to model. The unique architecture of Goodwin Hall, along with the vast amount of data it generates, make it a valuable testbed for the generalization of SHM methods to atypical civil structures. This paper will describe the instrumentation and processing strategy which incorporates simultaneous measurements from 82 high-sensitivity accelerometers. One hour of ambient excitation response data is processed using Principal Component Stochastic System Identification (SSI-PC), producing estimates of the first five building natural frequencies and mode shapes. The large number of sensors allows high degree of freedom resolution of the mode shapes. A comparison of the experimental results to a detailed finite element model shows that the stiffness of the structure was significantly underestimated by the building designers.

10168-85, Session 12A

Sparse reconstruction localization of multiple acoustic emissions in large diameter pipelines

Brennan Dubuc, Arvin Ebrahimkhanlou, Salvatore Salamone, The Univ. of Texas at Austin (United States)

An acoustic emission localization algorithm is presented, which is capable of localizing multiple acoustic emissions occurring closely in time. The presented method is based on the concept of sparse reconstruction, and is implemented on large diameter pipelines using helical guided ultrasonic waves. Unlike triangulation methods, which use only the first arrival waveform in a measured signal to perform localization, the presented algorithm uses information contained in the entire length of a signal. Using this approach, multiple acoustic emission events may be localized. In addition, the approach is able to localize for the cases in which a triangulation method may fail, due to multiple events occurring closely in

time. An experimental setup is designed for testing the performance of the presented approach in a large diameter pipe. Acoustic emissions are simulated by the standard pencil lead break to generate the experimental test data. As a benchmark, the sparse reconstruction approach is compared against the triangulation method for both isolated acoustic emissions and different cases of multiple acoustic emissions. It is demonstrated that sparse reconstruction localization yields comparable results to triangulation for isolated events, and greatly outperforms triangulation when multiple events are present. Two different solution methods for sparse reconstruction, namely orthogonal matching pursuit and basis pursuit, are compared in terms of their localization performance.

10168-86, Session 12A

Application of cross-correlation of scattered wave-field in stiffened aluminum panel

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To increase usage time and reduce the ground downtime of aircrafts, the concept of structural health monitoring has been introduced to enable condition-based maintenance, i.e., aircraft is inspected and repaired only when damage is detected. In the past years, structural health monitoring in plate-like structure is well studied, however, research in structures with complex geometry or reinforcement is still limited due to complicated wave reflections and changes of structural properties. To overcome this challenging problem, the Green's function through cross-correlation of scattered wave-field is reconstructed. This technique takes the advantage of the geometric complexity of structure which facilitates large scale reflection. The reconstructed Green's function is then processed through time-reversal imaging algorithm to show a full mapping of the structure. One and several pseudo damages are simulated in the structure to prove the ability of this technique to highlight the damage locations. First the concept is proved by simulation, then the feasibility of this technique is demonstrated through experimental work. The result indicated that the Green's function reconstruction using cross-correlation of recorded wave-field could be potentially applied to structures with even more complex reinforcement.

10168-87, Session 12A

Detection of surface cracking in steel Pipes based on vibration data using a multi-class support vector machine classifier

Samir Mustapha, American Univ. of Beirut (Lebanon); Ali Braytee, Univ. of Technology, Sydney (Australia); Lin Ye, The Univ. of Sydney (Australia)

In this study, we aimed at the development and verification of a robust framework for surface crack detection and assessment in steel pipes using measured vibration responses; with the presence of multiple progressive damage occurring in different locations within the structure. Feature selection, dimensionality reduction, and multi-class support vector machine were established for this purpose.

Nine damage cases, at different locations, orientations and length, were introduced into the pipe structure. The pipe was impacted 300 times using an impact hammer, after each damage case, the vibration data were collected using 3 PZT wafers which were installed on the outer surface of the pipe. At first, damage sensitive features were extracted using the frequency response function approach followed by recursive feature elimination for dimensionality reduction. Then, a multi-class support vector machine learning algorithm was employed to train the data and generate a statistical model. Once the model is established, decision values and distances from the hyper-plane were generated for the new collected data using the trained model. In addition, the effect of using raw data from a single sensor and multiple sensors combined on the precision of the prediction was investigated. It was found that the data used for training and testing must come from the same measurement source (sensor) otherwise the accuracy of prediction will drop significantly.

Overall, combining the raw data from all the sensors or using a single sensor for training and testing led to a very high accuracy reaching 98% in the assessment of the 9 damage cases used in this study.

10168-88, Session 12A

Detection and assessment of flaws in friction stir welded metallic plates

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Investigated is the ability of ultrasonic guided waves to detect and assess the quality of friction stir welds (FSW). AZ31B magnesium plates were friction stir welded. While process parameters of spindle speed and too feed were fixed, shoulder penetration depth was varied resulting in welds of varying quality.

Ultrasonic waves were excited at different frequencies using piezoelectric wafers and the fundamental symmetric (S0) mode was selected to detect the flaws resulting from the welding process. Wave signals attenuation after interaction with the welded zone was used to define a damage index (DI) measure. Due to the complexity of the captured wave signals, the S0 mode was separated using the "improved CEEMDAN" technique. Computed Tomography (CT) scanning was employed as an NDE technique to assess the actual weld quality. Experimentally derived DI measure values were plotted against CT-derived flaw volume resulting in a fairly linear fit. These findings were further validated using finite element analysis (FEA). The proposed approach showed high sensitivity of the S0 mode to internal flaws within the weld. As such, this methodology bears great potential as future classification method of FSW weld quality.

10168-89, Session 12B

Sensing and modeling of urban pollution and exposure

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Determining human exposure to air pollutants and its impact on human health is one of the most challenging tasks for managing energy systems in fixed and mobile infrastructure. This is largely due to high variability of pollutants composition and concentrations, both temporally and spatially, as well as highly varying patterns of human mobility. High resolution data on individual exposure to pollution has been unattainable. This is in part due to limitations of stationary, central site, monitoring programs, as well as lack of information about the mobility of exposed individuals. The impact of pollutants on human health has been estimated on aggregate levels, while pollutant levels have been derived from fixed monitoring stations, with limited spatial coverage. Fixed and sparsely placed data collectors do not accurately reflect the differences in air quality of an industrial neighborhood or a high density residential area, as compared to more suburban or rural areas. Here we present the results of a campaign measuring air parameters in five boroughs of NYC aggregated over seasons. The higher temporally resolved (hourly) measurements from fewer number of sites is used to create hourly map of the city at 300 meter spatial resolution. This information is then mapped against asthma records and mobility data for better understanding of the impact of the exposure to individuals.

10168-90, Session 12B

Structural health monitoring using a hybrid network of self-powered accelerometer and strain sensors

Amir H. Alavi, Hassene Hasni, Pengcheng Jiao, Nizar Lajnef, Michigan State Univ. (United States)

This paper presents a structural damage identification approach based on the analysis of the data from a hybrid network of self-powered accelerometer and strain sensors. Numerical and experimental studies are conducted on a plate with bolted connections to verify the method. Piezoelectric ceramic Lead Zirconate Titanate (PZT)-5A ceramic discs and PZT-5H bimorph accelerometers are placed on the surface of the plate to measure the voltage changes due to damage progression. Damage is defined by loosening or removing one bolt at a time from the plate. The results show that the PZT accelerometers provide a fairly more consistent behavior than the PZT strain sensors. While some of the PZT strain sensors are not sensitive to the changes of the boundary condition, the bimorph accelerometers capture the mode changes from undamaged to missing bolt conditions. The results corresponding to the strain sensors are better indicator to the location of damage compared to the accelerometers. The characteristics of the overall structure can be monitored with even one accelerometer. On the other hand, several PZT strain sensors might be needed to localize the damage.

10168-91, Session 12B

Simulation and experimental study on tensile force measurement of PS tendons using an embedded EM sensor

Byoungjoon Yu, Junkyeong Kim, Seunghee Park, Sungkyunkwan Univ. (Korea, Republic of)

The tensile force estimation PS tendons is in great demand on monitoring the structural health condition of PSC girder bridges. Measuring the tensile force of the PS tendons inside the PSC girder using conventional methods is hard due to its location. In this paper an embedded EM sensor based tensile force estimation of PS tendon was carried out by measuring the permeability of the PS tendons in PSC girder. The permeability is changed due to the induced tensile force by the magneto-elastic effect and the effect then lead to the gradient change of the B-H curve. An experiment was performed to obtain the signals from the EM sensor using three down-scaled PSC girder models. The permeability of PS tendons was proportionally decreased according to the increase of the tensile forces. To verify the experiment results, a simulation of tensile force estimation will be conducted in further study. Consequently, it is expected that both the experiment results and the simulation results increase the accuracy of the tensile force estimation, and then it could be one of the solution for evaluating the performance of PSC girder.

10168-92, Session 12B

Tunable mechanical monolithic sensors for real-time broadband distributed monitoring of large civil and industrial infrastructures

Fabrizio Barone, Gerardo Giordano, Univ. degli Studi di Salerno (Italy)

In the last decades the interest in the development of sensors for the implementation of low-frequency long-term monitoring systems aimed to assess the structural health status of large buildings and infrastructures like dams, bridges, sky-scrapes, oil platforms, etc., has largely increased. But although the basic underlying idea is very simple, actually the design of effective sensors is still a challenge. In fact, each structure, of any material and size, has its own intrinsic dynamics, characterized by vibration modes, generally at low frequencies and dependent on its present physical and geometrical characteristics: the mode of vibration of a structure is actually its “fingerprint” and one of the most effective way to highlight its health state. A structural test of a structure is aimed to verify the coincidence of its modes of vibration of the project with those measured: changes in the modal structures of a structure along the time indicate evolution of its dynamical behavior, that may prelude collapses and partial or total structural failures, as well as the appearance of additional modes that may be indicative of the presence of damages in the structural parts.

Among the different architecture of candidate sensors for this task, the Watt’s linkage is one of the most promising ones for the implementation of a new class of mechanical accelerometers (horizontal, vertical and angular), known as UNISA Folded Pendulum. In this paper, we present monolithic implementations of uniaxial and triaxial mechanical seismometers and accelerometers based on the UNISA Folded Pendulum mechanical configuration, optimized for low frequency characterization of sites (including underground sites) and structures as inertial sensor (seismometer). This mechanical architecture allows the design and implementation of very large band monolithic sensors (10^-7 Hz ÷ 10^2 Hz), whose sensitivities for the most common applications are defined by the noise introduced by their readouts (e.g. < 10^-12 m/sqrt(Hz) with classical LVDT readouts). These unique features, coupled other relevant properties like scalability, compactness, lightness, high directivity, frequency tunability (typical resonance frequencies in the band 10^-1 Hz ÷ 10^2 Hz), very high immunity to environmental noises and low cost make this class of sensors very effective for the implementation of uniaxial and triaxial seismometers and accelerometers.

Typical applications of this class of monolithic sensors are in the field of earthquake engineering, seismology, geophysics, civil engineering, characterization of sites (including underground sites), structures (e.g. buildings, bridges, historical monuments), and, in general, in all applications requiring large band-low frequency performances coupled with high sensitivities and compactness.

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10168-93, Session 12B

Monitoring the strength development of ultra high performance concrete using propagation characteristics of guided waves

Changgil Lee, Sungkyunkwan Univ. (Korea, Republic of); Sukhoon Pyo, Korea Railroad Research Institute (Korea, Republic of); John E. Bolander, Univ. of California, Davis (United States); Seunghee Park, Sungkyunkwan Univ. (Korea, Republic of)

In this study, the hardening process of ultra high performance concrete (UHPC) was monitored non-destructively using a single embedded sensor system and the characteristics of guided waves, especially the Lamb wave. Lamb wave propagation depends on the material properties of the medium and boundary conditions. Since the boundary conditions of the embedded sensor system continuously change during the hardening process of concrete materials, the measured characteristics of the propagating waves also vary. To understand the variations in wave propagation, the Lamb modes were decomposed using the polarization characteristics of piezoelectric sensors, which were used to measure wave responses. Additionally, a traditional penetration resistance method was adopted to estimate the time for phase transition of UHPC. The decomposed Lamb modes were compared to measurements of penetration resistance. The strength development of UHPC, with and without short-fiber reinforcement, was estimated using the variation of patterns of the decomposed Lamb modes after the phase transition. Based on the proposed methodology, which measures the propagation and variation of the Lamb waves, it is possible to estimate the time of phase transition and the strength development of UHPC.

10168-94, Session 12B

Theoretical and experimental study on finite element model updating of bridge using distributed macro-gauge strain sensing

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A finite model updating method that combines dynamic and static macro-gauge strain response is proposed for beam bridges. For this method, the objective function consisting of static macro-gauge stains and modal macro-strain parameter (frequency) is established, wherein the local bending stiffness, density and boundary conditions of the structures are selected as the design variables. The relationship between the macro-gauge strain and local stiffness was studied. It is revealed that the macro-gauge strain is in inverse proportion to the local stiffness covered by the macro-gauge strain sensor. This corresponding relation is important for the modification of the local stiffness based on the macro-gauge strain. The local and global parameters can be simultaneously updated. Then, numerical simulation and experiments were conducted to verify the effectiveness of the proposed method, and long-gauge fiber bragg grating sensors are applied to measure the macro-strain. The results show that the static deformation, macro-gauge strain and modal macro-strain can be well predicted by using the updating model.

10168-95, Session 12B

Measurement of greenhous gases in UAE by using Unmanned Aerial Vehicle (UAV)

Ali Abou-Elnour, Ajman Univ. of Science & Technology (United Arab Emirates)

The Greenhouse effect is caused by the function of greenhouse gases in the atmosphere, which is absorbing and emitting radiation within the thermal infrared range, this natural effect is contributing to the survival of life on earth by trapping and absorbing the heat of the sun to keep the earth temperature normal. According to the ministry of energy in United Arab Emirates, UAE released 199.65 million tons of Carbon dioxide and other greenhouse gases (GHG) in the year 2013. Primary greenhouse gases include carbon dioxide (CO2), methane (NH4), nitrous oxide (N2O), water vapor (H2O), and ozone (O3), each gas has its normal concentration in the atmosphere that will keep the greenhouse effect at normal levels. Human activities such as use of fossil fuels has increased the amount of greenhouse gases in the atmosphere, this causes the greenhouse effect to trap and absorb more heat on the earth causing what known as the global warming which cause lots of changes in our system like Climatic phenomena. It has been estimated that if greenhouse gas emissions continue at the present rate, Earth's surface temperature could exceed historical values as early as 2047, which will have harmful effects on ecosystems, and biodiversity. Carbon dioxide and methane are the most emitted gases from human activities so in order to decrease the effect of global warming we should monitor and restrict the emissions of gases from human activities.

Measurement data of GHG concentration are available in western countries using high technologies (Highly Instrumented Aircraft) which are relatively expensive. For most of the countries in the Middle East like the United Arab Emirates, which is known for its efforts in renewable energy and eco-friendly projects, a full set of accurate data which indicate the temporal and spatial variations of GHG concentration all over the country at different heights is still needed and required to be developed. The aim of the present work is to provide the ability to measure GHG on heights reaching up to 2000 meter using intelligent and low cost system. The design and implementation of the system will be carried out with commercial, but yet accurate sensors and other technologies to get accurate reading in any area independent of its nature.

To achieve the previous requirements, a special unmanned aerial vehicle (UAV) that will have the ability to reach the required height is going to be used. This will make measuring and monitoring GHG concentration easier. The choice of the hardware components depends on the requirements like speed, flight duration and thrust. Also in this stage the transmitter will be configured with the speed controllers. The first stage to the code of the flight controller is done using the Arduino microcontroller, an IMU sensor library, and PID controller algorithm to generate the required code for this project. The second stage is then carried out by testing the PID controller and calibration for PID gains for proper and smooth response.

In order to be able to continuously measure gases concentration on the required heights, we will make use of accurate gas sensors which can be easily integrated with the Arduino microcontroller to measure different gases concentrations at different heights. In addition, parameters like temperature, humidity, and pressure at that height will also be measured and recorded for additional sophisticated calculations. One of the most important features of the present system that all measurements will be recorded directly in a storage device unit (SD card) and will be accessed for research and monitoring purposes.

The obtained results are significant as we believe that our proposed system is an important one for environmental monitoring in UAE. The advances in wireless, microcontrollers, and sensing technologies will open a wide market of intensive and capillary environmental data acquisition, which are not limited only to gas concentrations, but also extended to measure temperature, humidity, aerosols, pollens, and all other similar parameters.

10168-140, Session 12B

Detecting subsurface features and distresses of roadways and bridge decks with ground penetrating radar at traffic speed

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This paper presents the detections of the subsurface features and distresses in roadways and bridge decks from the ground penetrating radar (GPR) data collected at traffic speed. This GPR system is operated at 2 GHz with the penetration depth of 60 cm in common road materials. The system can collect 1000 traces a second, has a large dynamic range and compact packaging. Using a four channel GPR array, dense spatial coverage can be achieved in both longitudinal and transversal directions. The GPR data contains significant information about subsurface features and distresses resulting from dielectric difference, such as distinguishing between new

and old asphalt, identification of the asphalt-reinforced concrete (RC) interface, and detection of rebar in bridge decks. For roadways, the new and old asphalt layers are distinguished from the dielectric and thickness discontinuities. The results are validated by surface images of the roads taken by the video camera. For bridge decks, the asphalt-RC interface is automatically detected by a cross correlation and Hilbert transform algorithms, and the layer properties (e.g., dielectric constant and thickness) can be identified. Moreover, the rebar hyperbolas can be visualized from the GPR B-scan images. Besides, the reflection amplitude from steel rebar can be extracted. It is possible to estimate the rebar corrosion level in concrete from the distribution of the rebar reflection amplitudes.

10168-97, Session 13

Stochastic subspace system identification using multivariate time-frequency distributions

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Structural health monitoring assesses structural integrity by processing the measured responses of structures. One particular group in the structural health monitoring research is to conduct the operational modal analysis and then to extract the dynamic characteristics of structures from vibrational responses. These characteristics include natural frequencies, damping ratios, and mode shapes. Deviations in these characteristics represent the changes in structural properties and also imply possible damage to structures. In this study, a new stochastic system identification is developed using multivariate time-frequency distributions. These time-frequency distributions are derived from the short-time Fourier transform and subsequently yield a time-frequency matrix by stacking them with respect to time. As the derivation in the data-driven stochastic subspace system identification, the future time-frequency matrix is projected onto the past time-frequency matrix. By exploiting the singular value decomposition, the system and measurement matrices of a stochastic state-space representation are derived. Consequently, the dynamic characteristics of a structure are obtained. As compared to the time-domain stochastic subspace system identification, the proposed method utilizes the past and future matrices with a lower dimension in projection. A spectral magnitude envelope can be applied to the time-frequency matrix to highlight the major frequency components as well as to eliminate the components with less influence. To validate the proposed method, a numerical example is developed. This method is also applied to experimental data in order to evaluate its effectiveness. As a result, performance of the proposed method is superior to the time-domain stochastic subspace system identification.

10168-98, Session 13

Structural damage detection using high dimension data reduction and visualization techniques

Jia-Hua Lin, Hsueh Wen, Chin-Hsiung Loh, National Taiwan Univ. (Taiwan)

Structural health monitoring (SHM) is considered as an incentive multi-disciplinary technology for conditional assessment of infrastructure system. However, most classical output-only system identification methods based on a stationary assumption fail to achieve reliable results under non-stationary scenarios. Numerous techniques from the disciplines of multivariate statistics and pattern recognition in the field of structural damage detection have been developed, such as stochastic subspace identification or null-space and subspace damage identification. Since most of the structural monitoring system is equipped with data vector of high dimensionality. In order to obtain the accurate structural damage assessment using such a dense array data, dimension reduction and data visualization will be investigated from which the structural damage detection can be easily identified

In this study a structural health monitoring method for damage identification and localization, which incorporated with the principal component analysis (PCA) based data compression and pattern recognition is developed. First, the frequency response function (FRF)-based damage assessment using PCA is used for de-noise. Then based on the de-noised FRF to construct the Sammon maps using all the measurements. Sammon's mapping is a nonlinear dimensional reduction algorithm to detect data structure, and referred to as a tool to project median FRF from high dimensional space onto a two dimensional space and visual the change among different damage situation. The results can provide information to identify damage severity. Finally, in cooperated with stochastic subspace identification (SSI) to identify the mode shapes and the change of flexibility matrix for damage localization, the damage location can be identified. Verification of the proposed methods using shaking table tests of two structures is demonstrated: One is focus on the damage of lower vibration modes and the other one is focus on the damage of high frequency modes.

10168-99, Session 13

Vibration analysis of lumped parameter systems via fractional order models

John Hollkamp, Fabio Semperlotti, Purdue Univ. (United States); Mihir Sen, Univ. of Notre Dame (United States)

This study explores the use of fractional differential equations to model the vibration of single (SDOF) and multiple degree of freedom (MDOF) discrete parameter systems. In particular, we explore methodologies to simulate the dynamic response of discrete systems having non-uniform coefficients (that is, distribution of mass, damping, and stiffness) by using fractional order models. Different approaches are explored in order to convert a traditional integer order model into a fractional order model able to match, often times exactly, the dynamic response of the initial integer order system. Analytical and numerical results show that, under certain conditions, an exact match is possible and the resulting differential models have both frequency-dependent and complex fractional order. The presented methodology is practically equivalent to a model order reduction technique that is able to match the response of non-uniform MDOF systems to simple SDOF or MDOF fractional systems. The implications of this type of modeling approach will be discussed.

10168-101, Session 13

A new correlation-based damage identification method using experimental modal information

Khac Duy Nguyen, Tommy H. T. Chan, David P. Thambiratnam, Theanh Nguyen, Queensland Univ. of Technology (Australia)

A recently developed method based on change in ratio of geometric modal strain energy to eigenvalue (GMSEE ratio) has shown its good performance in locating and quantifying damage. As an effort to improve the effectiveness of this method regarding fewer modes used, this study presents a new method using modal strain energy (MSE) and natural frequency in a similar combined manner. A new vibration parameter, ratio of MSE to eigenvalue (MSEE ratio), has been developed and its change due to stiffness reduction has been approximately formulated using a sensitivity matrix. For damage detection, the multiple damage location assurance criterion (MDLAC) is modified considering both elemental MSEE ratio and total MSEE ratio. The genetic algorithm (GA) is utilized to search the maximum MDLAC which represents the damaged state. A numerical 2-D truss bridge is used to verify the proposed method and to compare the method with a recently developed correlation method using change in GMSEE ratio. Results indicate that the new method can identify damage

with better accuracy compared to the existing method when fewer modes are used.

10168-102, Session 13

Wavelet-based adaptive meshing for electrical impedance tomography

Fabio Semperlotti, Purdue Univ. (United States) and Univ. of Notre Dame (United States); Jie Yang, Univ. of Notre Dame (United States)

In tomographic methods, such as Electrical Impedance Tomography (EIT), the sensitivity and resolution of the reconstruction strongly depend on the numerical model used to predict the response of the object under analysis. In order to capture highly localized features, high density computational meshes are typically needed. Dense meshes result in increased computational time and, most important, in an increased number of parameters to be reconstructed. This latter aspect often impacts the conditioning of the underlying mathematical problem therefore deteriorating the quality of the reconstruction. Adaptive mesh refinement can provide a powerful approach to this class of problems by drastically increasing the global accuracy at a greatly reduced computational cost. This study explores the use of a class of adaptive meshing techniques, namely the Wavelet Adaptive Mesh Refinement (WAMR), to improve the EIT computational performance and resolution as well as the accuracy to highly spatially localized features. The fundamental theory behind the WAMR algorithm will be presented and its application to EIT will be discussed based on a series of numerical simulations.

10168-139, Session 13

A distributed cloud-based cyberinfrastructure framework for integrated bridge monitoring

Seongwoon Jeong, Stanford Univ. (United States); Rui Hou, Jerome P. Lynch, Univ. of Michigan (United States); Hoon Sohn, KAIST (Korea, Republic of); Kincho H. Law, Stanford Univ. (United States)

This paper describes the development of a scalable cyberinfrastructure framework for seamless integration of the diverse data involved in bridge monitoring. Bridge monitoring applications include many different components, such as structural health monitoring (SHM) system, bridge management system (BMS), and various analysis tools. In current practice, these components are isolated from each other and information sharing across systems is very limited. Information sharing and system integration would facilitate meaningful use of data and enhance bridge operation and maintenance and public safety. In this paper, we propose a scalable and flexible cyberinfrastructure to handle the massive data sets from diverse sources in an integrated manner. Cloud computing and distributed database systems are employed to facilitate scalable, flexible, fault-tolerant, high performing and cost-effective management of the bridge information. The framework manages not only sensor data, but also other relevant information including bridge engineering model, inspection information, and image data collected at bridge locations. We define data schema for storing these data with links between related data entities. The framework provides an integrated web interface where authorized users can access to the data storage. In addition, the framework includes an automated system to capture events on the bridge behavior based on the sensor data. The automated system notifies the captured events to bridge managers along with relevant information and analysis results via a notification system. The proposed framework is implemented for the monitoring of the bridges on I275 Corridor in the State of Michigan.

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10169-1, Session 1

SAR image processing techniques for damage detection of FRP-concrete systems

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Electromagnetic imaging enables researchers and engineers to assess the surface and subsurface condition of concrete structures using radar and microwave sensors. Among existing radar imaging methods, synthetic aperture radar (SAR) imaging offers flexible resolution for various purposes in condition assessment. In this paper, two novel SAR image processing techniques are reported for the subsurface condition assessment of FRP(fiber reinforced polymer)-strengthened concrete systems; mathematical morphology (MM) and the K-R-I transform. Glass FRP (GFRP) and carbon CFRP (CFRP) strengthened concrete cylinders were used as examples to demonstrate the performance of both techniques. A 10GHz continuous wave imaging radar sensor was applied for generating SAR images of FRP-concrete cylinders. Physical radar measurements were carried out inside an anechoic chamber. From our experimental results, it is found that both techniques are capable of quantifying SAR images for condition assessment.

In MM, Euler's number can be used to quantify the global change of SAR images. Variation of Euler's number also indicates the minimum amount of radar measurements in order to achieve consistent assessment result. In addition, determination of a threshold value for finding the representative Euler's number is instrumental to the success of the MM technique. In the K-R-I transform, the coefficient of correlation of K-R-I curves of SAR images can be used for monitoring subsurface changes in FRP-concrete systems. The K-R-I curve of each SAR image can capture the local features of SAR images by depicting the size and distribution of SAR amplitudes.

10169-2, Session 1

High-resolution nondestructive testing of multilayer dielectric materials using wideband micro- and millimeter-wave synthetic aperture radar imaging

Tae Hee Kim, Robin James, Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Fiber Reinforced Polymer or Plastic (FRP) composites have been rapidly increasing in the aerospace, automotive and marine industry, or civil engineering, because these composites show superior characteristics such as outstanding strength and stiffness, low weight, as well as anti-corrosion and easy production. Generally, the advancement of materials calls for correspondingly advanced methods and technologies for inspection and failure detection during production or maintenance, especially in the area of nondestructive testing.

Among numerous inspection techniques, microwave method can be effectively used for Nondestructive Testing (NDT) purposes of FRP composites. FRP composite materials can be produced using various structures and materials, and various defects or flaws due to environmental conditions encountered during operation. However, reliable, low-cost, and easy-to-operate NDT methods have not been developed and tested. FRP composites are usually produced as multilayered structures consisting of fiber plate, matrix and core. Therefore, typical defects appearing in FRP composites are disbondings, delaminations, object inclusions and certain kinds of barely visible impact damages.

In this paper, we propose a microwave NDT method, based on synthetic aperture radar (SAR) algorithm for stand-off imaging of internal cracks. When a microwave signal is incident on a multilayer dielectric material, the reflected signal provides a good response to interfaces and transverse cracks. An electromagnetic wave model is introduced to delineate interface widths or defect depths from the reflected waves. For the purpose of numerical analysis and simulation, multilayered composite samples with various artificial defects are assumed, and their SAR images are obtained and analyzed using a variety of high-resolution wideband waveforms.

10169-3, Session 1

Rough ground surface clutter removal in air-coupled ground penetrating radar data using low-rank and sparse representation

Yu Zhang, Dryver R. Huston, Tian Xia, The Univ. of Vermont (United States)

Ground penetrating radar (GPR) is a non-destructive evaluation technique specifically effective for detecting buried objects. Comparing with the ground-coupled GPR system, the air-coupled GPR sensing provides the benefit of high speed survey due to the large standoff distance between the antennas and the ground surface. Whereas the large standoff distance leads to significant propagation losses. As a result, the effective reflection signal from the subsurface object is greatly reduced. In order to extract the weak scattering from the subsurface object, removal of the strong ground surface clutter is an issue of predominance. Many clutter removal methods have been investigated in the literature, which generally deal with relatively flat ground surfaces. When the ground surface conditions are complicatedly rough, the effectiveness of many clutter removal algorithms are degraded. To tackle such problems, in this paper, a low-rank and sparse representation based technique is explored to remove the clutter produced by rough ground surface reflection. For rough or non-flat ground surface, the surface clutter components in different A-Scan traces are not aligned on the depth axis. To compensate for these misalignments so as to facilitate clutter removal, in this study, a set of matrix transformations is integrated into the low-rank and sparse representation processing approach. The proposed technique aims to decompose the GPR data matrix into two sub-matrices: a low-rank matrix whose column data record the ground clutter in A-Scan traces upon alignment adjustment, and a sparse matrix that feature the subsurface object. The decomposition matrix and the transformation matrix set are uniquely derived through iterative linearization of the rank and sparsity constraints. The effectiveness of the proposed rough ground surface clutter removal method will be evaluated through simulations and laboratory experiments.

10169-4, Session 1

Detecting and locating steel rebars inside concrete using synthetic aperture radar images

Swinderjit Singh Litt, Jones Owusu Twumasi, Tzu-Yang Yu, Univ. of Massachusetts Lowell (United States)

Detecting and locating subsurface steel rebars in reinforced concrete (RC) structures is important to RC structures for corrosion monitoring. Microwave and radar NDE utilizing imaging algorithms has demonstrated to be an effective approach for subsurface sensing of RC structures. In this paper, we report our research on the detection and localization of subsurface steel rebars inside concrete using synthetic aperture radar (SAR) images. In this experimental work, one plain concrete beam (10.16 cm by 15.24 cm by 45.72 cm) and one RC beam were manufactured to consider the effect of concrete cover on subsurface steel rebar detectability using SAR images. A monostatic 10 GHz imaging radar system with a bandwidth of 1.5 GHz was used. Six concrete covers (2.29 cm, 4.06 cm, 5.08 cm, 6.60 cm, 8.38 cm and 10.16 cm) were considered in the design of the RC beam with two No. 4 rebars located at different depths. SAR imaging range was 30 cm and 40 cm for the cross-range. All SAR images were collected inside an anechoic chamber. From our result, it was found that the presence of two subsurface steel rebars is detected by scattering signals in SAR images. Locations of steel rebars were predicted by using the center of scattering signals in SAR images.

10169-5, Session 2

Application of ground-penetrating radar in bridge condition assessment

Azin Shakibabarough, Ashutosh Bagchi, Concordia Univ. (Canada)

Safety evaluation and health of the bridge is an important issue for the government. Traditional visual inspection methods have been applied for monitoring the condition of the bridge and any deterioration and defect of bridges have been identified with traditional techniques. But, traditional techniques for bridge condition assessment are usually time consuming and full of human errors and also cause to traffic. Therefore, developing a Non-destructive evaluation technique greatly solves the deficiencies of traditional bridge condition evaluation techniques. Nowadays, Ground Penetrating Radar (GPR) is considered as one of best methods among Non-destructive Evaluation (NDE) techniques for evaluating of the health of bridge deck. The main purpose of this paper is to investigate the application of GPR in bridge condition assessment and determination of appropriate threshold signal in GPR image processing. Interpretation of GPR image is the most important part of this process. Therefore, application of image processing technique for making GPR data into understandable visual representations is also investigated.

10169-6, Session 2

Measurement of electromagnetic properties of powder and solid metal materials for additive manufacturing

Evgueni I. Todorov, EWI (United States)

The lack of validated nondestructive evaluation (NDE) techniques for examination before, during and after additive manufacturing (AM) component fabrication is one of the obstacles on the way of rapid AM introduction to critical applications. Knowledge of electromagnetic properties of powder (e.g. feedstock) and solid AM metal components is necessary to evaluate and deploy electromagnetic NDE modalities for examination of AM components. The objective of this research study was to develop and implement techniques for measurement of powder and solid metal electromagnetic properties.

Three materials were selected - Inconel 625, duplex stainless steel 2205, and carbon steel 4140. The powder properties were measured with alternate current (AC) model based eddy current technique and direct current (DC) resistivity measurements. The solid metal properties were measured with DC resistivity measurements, DC magnetic techniques, and AC model based eddy current technique. Initial magnetic permeability and electrical conductivity were acquired for both powder and solid metal. Additional magnetic properties such as maximum permeability, coercivity, retentivity, and others were acquired for 2205 and 4140. Two groups of specimens were tested along the build length and width respectively to investigate for possible anisotropy.

There was not significant difference or anisotropy when comparing measurements acquired along build length to those along the width. A trend in AC measurements might be associated with build geometry. Powder electrical conductivity was very low and difficult to estimate reliably with techniques used in the study. The agreement between various techniques was very good where adequate comparison was possible.

10169-7, Session 3

Feasibility study of buried non-metallic object detection using Unmanned Aerial Vehicle (UAV) mounted ground penetrating radar

Yu Zhang, Dylan Burns, Dan Orfeo, The Univ. of Vermont (United States); Jonathan S. Miller, White River Technologies, Inc. (United States); Dryver R. Huston, Tian Xia, The Univ. of Vermont (United States)

Ground penetrating radar (GPR) has been proved as an effective device for detecting buried objects that have little or no metal content, such as plastic, ceramic and concrete pipes. Comparing to hand-held and vehicle-mounted GPR, the use of unmanned aerial vehicle (UAV) in near-surface sensing provides the benefit of contactless survey on a large area in a short period of time, which will reduce the risk of entering the inaccessible or hazardous areas for GPR operators. In this paper, the feasibility of buried non-metal object detection using UAV-mounted GPR is studied and tested. In buried object detection, the GPR signal undergoes various losses in its propagation path from the transmitter to the receiver, which includes spreading loss in air, transmission coupling loss at the ground surface, subsurface material attenuation loss, and target scattering loss. Due to the large standoff distance between antennas and the ground surface, the UAV-mounted GPR has larger spreading loss than hand-held GPR and vehicle-mounted GPR. Moreover, for non-metal object detection, the plastic target or targets of low metal content have similar dielectric property to the buried medium, which also results in difficulty for accurate detection using UAV-mounted GPR.
In this paper, the analytical study of signal losses in its propagation path is performed for UAV-mounted GPR non-metal object detection scenario. Both GPR simulation and real GPR lab experiments on non-metal object buried in a sandbox are performed and compared with the analytical study results. In the GPR detection experiments, transmitter and receiver antennas with various realistic heights and angles for UAV setup are tested. Different non-metal objects with dielectric constants higher and lower than the burying sand are used as the targets under test. Buried objects are scanned with and without surface clutter, which is a layer of rocks on the rough sand surface. The experimental results show the feasibility of UAV-mounted GPR for detecting buried non-metal objects.

10169-8, Session 3

Unmanned aerial vehicle acquisition of three-dimensional digital image correlation measurements for structural health monitoring of bridges

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Civil engineering structures such as bridges, buildings, and tunnels continue to be used despite aging and deterioration well past their design life. In 2013, the American Society of Civil Engineers (ASCE) rated the state of the U.S. bridges as mediocre, despite the $12.8 billion USD annually invested. Traditional inspection and monitoring techniques may produce inconsistent results, are labor intensive and too time-consuming to be considered effective for large-scale monitoring. Therefore, new structural health monitoring systems must be developed that are automated, highly

accurate, minimally invasive, and cost effective. Three-dimensional (3D) digital image correlation (DIC) systems possess the capability of extracting full-field strain, displacement, and geometry profiles. Furthermore, as this measurement technique is implemented within an Unmanned Aerial Vehicle (UAV) the capability to expedite the optical-based measurement process is increased as well as the infrastructure downtime being reduced. Multiple profiles sharing common reference points can then be both stitched to additional DIC generated profiles, as well as larger 3D surface models generated from photogrammetry techniques. These resulting integrity maps of the structure of interest can be easily interpreted by trained personal. Within this paper, the feasibility of performing DIC measurements using a pair of cameras installed on a UAV is shown. Performances are validated through in-flight measurements. Also, full-field displacement monitoring, 3D measurement stitching, and 3D point-tracking techniques are employed in conjunction with 3D mapping and data management software. The results of these experiments show that the combination of autonomous flight with 3D DIC and other non-contact measurement systems provides a highly valuable and effective civil inspection platform.

10169-9, Session 3

The design and implementation of a remote UAV-based mobile health monitoring system

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Unmanned aerial vehicles (UAVs) play increasing roles in structure health monitoring. With growing mobility in modern Internet-of-Things (IoT) applications, the health monitoring of moving structures becomes an emerging application. In this paper, we develop an effective UAV-carried vision-based monitoring system that allows a UAV to continuously track and monitor a mobile structure (target) and transmit back the monitoring information in real-time from a remote location. Based on a novel vision-based lead-follower tracking algorithm, the monitoring system uses a simple UAV-mounted camera and requires only a single feature on the mobile target to for robust target detection and tracking. The robust and computation-effective tracking algorithm based on a single feature is a significant improvement over existing vision-based lead-follower tracking systems that either have poor tracking performance using a single feature on the target or have improved tracking performance at a cost of the equipment of multiple features. In addition, a UAV-carried aerial networking infrastructure using directional antenna is used to enable robust real-time transmission of monitoring video over a long distance. Automatic heading control is used to self-align headings of directional antennae to enable robust communication in mobility. Compared to existing omni-based communication systems, the directional communication infrastructure significantly increases communication range of the monitoring systems. In this paper, we develop the integrated modeling framework of cameras and mobile systems, design the tracking algorithm, develop a testbed of UAVs and mobile platforms, and evaluate the performance of the system through both simulation and field tests.

10169-10, Session 4

Ultralight 3D composite metamaterials with high defect tolerance and ductility

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It has been a long research and engineering pursuit to create lightweight and mechanically robust and energy efficient materials with interconnected porosity. These cellular materials are desirable for a broad range of applications including structural components, lightweight transportation, heat exchange, catalyst supports, battery electrodes and biomaterials.

However, the required outstanding properties have remained elusive on lightweight materials (<10kg/m^3), constrained by the inherent coupling of material properties and the lack of suitable processes to generate these artificial materials. For example, graphene aerogels have among the lowest record densities ~1kg/m^3, but their strength have been degraded to tens to hundreds of Pascal (<10^-8 of that of carbon nanotubes). The attainment of low density has come with a price --- significant reduction of bulk scale properties.

We present the design, manufacturing and defect tolerance study of a new class of ultralight, three-dimensional multi-functional architected materials. These 3D bulk metamaterials (polymer, metal, ceramic and combinations thereof) possess weight density comparable to that of carbon aerogel, but with over 10^4 higher stiffness and strength. By designing and studying their hierarchical architectures, material compositions and feature sizes spanning multiple length-scales, we create a wide range of decoupled material properties such as programmable stiffness, tunable strength and fracture toughness as well as programmable possion ratio. With the possibility of incorporating precise control of topological architectures across length-scale sets as well as prediction and optimization of their defect tolerance, we enter into a paradigm where nanoscale material properties can be harnessed and made accessible in large scale objects, opening a wide range of applications of these materials in energy, health care and flexible electronics.

10169-11, Session 4

Prognostic investigation of galvanic corrosion precursors in aircraft structures and their detection strategy

Robin James, Tae Hee Kim, Ram M. Narayanan, The Pennsylvania State Univ. (United States)

Aluminum alloys have been the dominant materials for aerospace construction in the past fifty years due to their light weight, forming and alloying, and relative low cost in comparison to titanium and composites. However, in recent years CFRPs (carbon fiber reinforced polymers) and honeycomb materials have been used in aircrafts in the quest to attain lower weight, high temperature resistance and better fuel efficiency. When these two materials are coupled together, the structural strength of the aircraft is unparalleled, but this comes at a price - galvanic corrosion. Previous experimental results have shown that when CFRP composite materials are joined with high strength aluminum alloys (AA7075-T6 or AA2024-T3), galvanic corrosion occurs at the material interfaces and the aluminum is in greater danger of corroding, particularly since carbon and aluminum are on the opposite ends of the galvanic series.

This paper gives a synopsis of the occurrence of the recognizable precursors of galvanic corrosion when CFRP plate is coupled to an aluminum alloy using SS-304 bolts and exposed to environmental degradation creating a lot of concerns for aircraft structural reliability. A non-contact microwave NDT technique with a suitable standoff distance is explored to detect corrosion defects that appear at the interface of this galvanic couple. Radar signals operating at microwave and millimeter wave frequencies can be used to detect these corrosion defects as aberrations that are present at the interior of the structure. An empirical relationship between corrosion properties and dielectric properties of the corrosion products can be developed to make a prognostic assessment of corrosion growth.

10169-12, Session 4

Structural health monitoring of inflatable structures for MMOD impacts

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Inflatable structures for space habitat are highly prone to damage caused by micrometeoroid and orbital debris impacts. Although the structures are

effectively shielded against these impacts through multiple layers of impact resistant materials, there is a necessity for a health monitoring system to monitor the structural integrity and damage state within the structures. Assessment of damage is critical for the safety of personnel in the habitat, as well as predicting the repair needs and the remaining useful life of the habitat. In this paper, we propose a unique impact detection and health monitoring system based on hybrid nanocomposite sensors. The sensors are composed of two fillers, carbon nanotube sheet and coarse graphene platelets with an epoxy matrix material. The flexible nanocomposite sensors are fabricated using the vacuum assisted resin infiltration process followed by curing. The electrical conductivity of these nanocomposite sensors is highly sensitive to any holes and damage presented in the structure. The sensitivity of the sensors to the presence of 3mm holes resulted due to an event of impact is evaluated using four probe electrical resistivity measurements. An array of these sensors when sandwiched between soft good layers in a space habitat can act as a damage detection layer for inflatable structures. An algorithm is developed to determine the event of impact, its severity and location on the sensing layer for active health monitoring.

10169-13, Session 4

In-field implementation of impedance-based structural health monitoring for insulated rail joints

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Track defects are a major safety concern for the railroad industry. Among the different track components, insulated rail joints, which are widely used for signaling purposes, are considered as a weak-link in the railroad track. Several joint-related defects have been identified by the railroad community, including rail wear, torque loss and joint-bar breakage. Current track inspection techniques rely on manual and visual inspection or specially equipped testing carts, which is costly, time consuming, traffic disturbing, and prone to human error.

To overcome the aforementioned limitations, the feasibility of utilizing impedance-based Structural Health Monitoring (SHM) for insulated rail joints is investigated in this work. For this purpose, an insulated joint kit, provided by Koppers Inc., is instrumented with piezoelectric transducers and assembled with 136 AREA rail plugs. The instrumented joint is then installed and tested in the field at the Facility for Accelerated Service Testing, Transportation Technology Center Inc. The effects of environmental and operating conditions on the measured impedance signature are investigated through a set of experiments conducted at different temperatures and loading conditions. The capabilities of impedance-based SHM to detect several joint-related damage types are also studied by introducing reversible mechanical defects to different joint components.

10169-14, Session 4

Characterization of the spatial piezoresistivity of inkjet-printed carbon nanotube thin films for strain-state sensing

Patrick Gruener, Yingjun Zhao, Martin Schagerl, Johannes Kepler Univ. Linz (Austria)

Carbon nanotube (CNT)-suspended polymer solution can be inkjet-printed into a thin sheet consisting uniform morphology and consistent electrical properties. When subjected to a loading scheme, the thin film's inherent electrical property changes in tandem with the deformation. This unique property makes CNT thin films the appropriate candidate for strain sensing applications. Recent studies on characterizing the gage factor of CNT-embedded thin films are limited to learning the material's resistance change along the loading direction only. However, research interests on strain measurement of a structure have shifted from point-based interrogation to spatial strain-state monitoring. To use a CNT thin film as a spatial strain-state sensor, one has to characterize its anisotropic resistivity also in non-loading directions. In this study the resistivity-strain constitutional relation of an inkjet-printed CNT thin film is established based on theories for semi-conductive materials. The development takes linear elasticity approach on anisotropic material responses. The 2D piezoresistivity tensors are characterized via monotonic tensile tests on free-standing thin films. Experimental validations are performed by implementing tensor analysis of piezoresistivity in electrical impedance tomography (i.e., an algorithm reconstructs a body's spatial conductivity based on boundary voltage measurements) to illustrate its spatial strain-state distribution.

10169-15, Session 4

Structural health monitoring of an 3D printed shape memory alloy structure via embedded fiber optic sensors

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The development of high definition fiber optic sensors enables the measurement of internal strains and temperatures in shape memory alloy (SMA) structures that are not available via conventional external metrologies. To demonstrate the capabilities of these novel self-sensing actuators, optical fibers are embedded into an SMA constant stress beam. The SMA beam is manufactured in the martensitic state utilizing the selective laser melting (SLM) method and includes four interior channels, two at the neutral plane and two slightly offset from the neutral plane. The two pairs of optic fibers are utilized to measure the strain and temperatures at multiple points throughout the beam. The fibers are inserted into the channels and fibers intended for strain measurement are coated with epoxy; fibers for measuring temperature are left free relative to the deformation of the beam. The proposed novel experiment considers the SMA beam as a cantilever beam with a concentrated load at the free end. A patch heater resistively heats the beam leading to a temperature-induced phase transformation from martensite to austenite, affecting shape recovery and thus leading to the generation of actuation work. A laser and an infrared camera are also utilized in order to measure the free edge displacement and the beam surface temperature. Expected results include strains generated during phase transformation along the ,neutral plane, where linear theories predict no strains, as well as strains and temperatures at other points throughout the active material beam component.

10169-16, Session 4

Carbon nanotube based structural health monitoring for fiber reinforced composite materials

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As one of the most promising structural materials in modern society, fiber-reinforced composite materials are being widely used in aerospace, automotive, and civil fields due to the high strength, high stiffness and low density. However, during the overall life span of fiber-reinforced composite materials the existing external loading will inevitably result in multiple failure modes, ranging from micro-level to macro-level, such as the occurrence of micro and transverse matrix cracks, fiber breakage, fiber-matrix de-bonding, delamination, .etc. The failures negatively affect the structural performance, which leads to an emerging need for a reliable, robust, and

versatile structural health monitoring method designed to increase the reliability of composite materials. The recent advances in the macroscopic forms of carbon nanotube materials offer the potential to combine the novel nanotechnology and the conventional structural health monitoring techniques. Aiming at exploring and obtaining the data of failure, durability, and damage tolerance of fiber composites, this research was conducted to fabricate fiber composite panels with integrated carbon nanotubes for strain sensing and damage detection based on their spatial electrical properties change. Multiple kinds of mechanical tests were performed while the response behavior was recorded and the data were then analyzed to evaluate the sensing capability. Damages are initially induced onto the prototype panel and the damage detection sensitivity is measured. As shown by the results, this new structural health monitoring design is proven to be reliable and highly-sensitive to detect failures at different levels. The theoretical foundation is that cracks largely change the local electric field and also alter the electrical / magnetic properties of the composite system. The manufacturing process of integrating the carbon nanotubes into the composite system has the influence on the performance of the detection sensitivity and repeatability, and an optimal design is proposed in this paper.

10169-17, Session 4

Detecting the water absorption in glass fiber reinforced epoxy (GFRE) composite pipes via an electrical capacitance sensors

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One of the major problems in glass fiber reinforced Epoxy (GFRE) composite pipes is the durability under water absorption. This condition is generally recognized to cause degradations in strength and mechanical properties. Therefore, there is a need for an intelligent system for detecting the absorption rate and computing the mass of water absorption (M%) as a function of absorption time (t). The present work represents a new non-destructive evaluation (NDE) technique for detecting the water absorption rate by evaluating the dielectric properties of glass fiber and epoxy resin composite pipes subjected to internal hydrostatic pressure at room temperature. The variation in the dielectric signatures is employed to design an electrical capacitance sensor (ECS) with high sensitivity to detect such defects. ECS consists of 12 electrodes mounted on the outer surface of the pipe. Radius-electrode ratio is defined as the ratio of inner and outer radius of pipe. A finite element (FE) simulation model is developed to measure the capacitance values and node potential distribution of ECS electrodes on the basis of water absorption rate in the pipe material as a function of absorption time. The arrangements for positioning12-electrode sensor parameters such as capacitance, capacitance change, and change rate of capacitance are analyzed by ANSYS and MATLAB to plot the mass of water absorption curve against absorption time (t). An analytical model based on A Fickian diffusion model is conducted to predict the saturation level of water absorption (M_S) from the obtained mass of water absorption curve. The FE results are in excellent agreement with the analytical results and experimental results available in the literature, thus, validating the accuracy and reliability of the proposed expert system.

10169-18, Session 5

The challenges and opportunities in lightweight materials and propulsion materials for vehicle applications *(Keynote Presentation)*

H. Felix Wu, U.S. Dept. of Energy (United States)

The U.S. Department of Energy's Vehicle Technologies Office (VTO) supports research, development, and deployment of efficient and sustainable highway transportation technologies that will improve fuel economy and enable America to use less petroleum. These technologies, which include plug-in electric vehicles (also known as PEVs or electric cars), batteries, electric drive technologies, advanced combustion engines, lightweight materials, and alternative fuels, will increase Americans' mobility and energy security, while lowering costs and reducing environmental impacts. VTO collaborates with industry leaders through partnerships like U.S. DRIVE (Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability) and 21st Century Truck, to develop and deploy advanced vehicle technologies, including highly efficient combustion engines, lightweight materials, and electric drive vehicles. These technologies can lead to significant fuel economy improvements and replace oil with domestic fuels, setting the foundation for clean, efficient, sustainable, and cost-competitive vehicles.

Materials play a major role in the U.S. DRIVE Partnership by enabling vehicle lightweighting of structures and systems, thereby improving fuel economy and reducing demands on the vehicle powertrain and ancillary systems (e.g., braking). The Materials Technical Team (MTT) focuses primarily on reducing the mass of structural systems such as the body and chassis in light-duty vehicles (including passenger cars and light trucks). Mass reduction also enables improved vehicle efficiency regardless of the vehicle size or propulsion system employed. The MTT strategy continues to focus on stretch but realistic goals and objectives to develop lightweight, high-performance, cost-effective structural materials for vehicle lightweighting. An integral part of this strategy is to engage the steel, aluminum, magnesium, carbon fiber, polymer composite, and plastic industries while working closely with suppliers to develop the infrastructure of advance manufacturing enablers for forming, casting, molding, joining, and assembly of light materials systems for automotive applications. The MTT strategy includes delivery of computational tools and methods with the goal of reducing the time and cost of developing and validating new materials, material processing methods, and manufacturing techniques and technologies. This includes tools capable of predicting the performance of materials, joints, and parts to optimize performance and mass. Working closely with national laboratories, academic institutions, and industrial research laboratories, the integration of constitutive models ranging from fundamental alloy to advanced manufacturing process methods plays an integral part of the MTT strategy.

In this paper, the author will give an overview on materials technology program including lightweight materials and propulsion materials. He will also discuss the challenges and opportunities in utilizing NDE/SHM technologies that could fit into the materials technology program in Vehicle Technologies Office at the U.S. Department of Energy.

10169-19, Session 5

Online resistance spot weld NDE using infrared thermography

Jian Chen, Zhili Feng, Oak Ridge National Lab. (United States)

Welding is an essential technology in auto-body structure assembly. On average, a passenger vehicle is assembled with 4,000 to 6,000 resistance spot welds (RSWs). Today, the automakers primarily rely on a destructive method to ensure weld integrity at predetermined time intervals (usually once per shift). It is an expensive and labor-intensive procedure. The very nature of the post-production destructive test means that only a few welds can be sampled for quality. Most RSWs in a car are never checked. As the automotive industry moves toward body structures with more advanced high strength steels (AHSS) and aluminum alloys, the destructive method will be less reliable and more costly, because these welds will be more difficult to open. Despite extensive R&D efforts over the years, nondestructive weld quality inspection has remained a critical need in the auto industry, largely due to the unique technological and economic constraints of the auto production environment.

Recently, a new online RSW NDE technique based on infrared (IR) thermography has been developed. It is capable of both real-time online (during welding) and post-weld online/offline (after welding) inspections. The system mainly consists of an IR camera and a computer program with proprietary thermal imaging analysis algorithms integrated into existing production lines. For real-time inspection, the heat flow generated from the welding process (with temperature exceeding 1000°C) is monitored by the IR camera. For post-weld inspection, a novel auxiliary heating device is applied to locally heat the weld region, resulting in temperature changes on the order of 10°C, and the transmitted heat flow is monitored. Unlike the conventional IR NDE method that requires surface coating to reduce the influence of unknown emissivity, the new method can be applied on as-is bare metal surface thanks to the unique “thermal signatures” extracted from infrared thermal images, which positively correlates to weld quality with a high degree of confidence. The new method can be used to reliably detect weld size, surface indents and defects such as cold weld with sufficient accuracy for welds made from various combinations of materials, thickness, stack-up configuration, surface coating conditions and welding conditions.

10169-20, Session 5

Development of nanoparticle embedded sizing for enhanced structural health monitoring of carbon fiber composites

Christopher C. Bowland, Amit K. Naskar, Oak Ridge National Lab. (United States)

Carbon fiber composites experience sudden, catastrophic failure when exposed to sufficient stress levels and provide no obvious visual indication of damage before they fail. With the commercial adoption of these high-performance composites in structural applications, a need for in-situ monitoring of their structural integrity is paramount. Therefore, ways in which to monitor these systems has gathered research interest. A common method for accomplishing this is measuring through-thickness resistance changes of the composite due to the fact that carbon fiber composites are electrically conductivity. This provides information on whole-body stress levels imparted on the composite and can help identify the presence of damage. However, this technique relies on the carbon fiber and polymer matrix to reveal a resistance change. Here, an approach is developed that increases damage detection sensitivity. This is achieved by developing a facile synthesis method of integrating semiconducting nanomaterials, such as silicon carbide, into carbon fiber sizing. The piezoresistive effect exhibited by these nanomaterials provides more pronounced resistance changes in response to mechanical stress as compared to carbon fiber alone. This is investigated through fabricating a unidirectional composite and subsequently monitoring the electrical resistance during mechanical testing. By establishing this route for integrating nanomaterials into carbon fiber composites, various nanomaterials can see future composite integration to realize novel properties.

10169-21, Session 5

Structural health monitoring of compression connectors for overhead transmission lines

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Two-stage aluminum conductor steel-reinforced (ACSR) compression connectors are extensively used in US overhead transmission lines. The connectors are made by crimping a steel sleeve onto the steel core and an aluminum sleeve over the aluminum conductive strands. The connectors are designed to operate at temperatures up to 125^oC but their performance has been increasingly degraded because of overloading of lines. Currently, electric utilities conduct routine line inspections using thermal and electric measurements. However, information about the structural integrity of connectors cannot be obtained.

The structural health monitoring (SHM) of compression connectors has been studied by using electro-mechanical impedance (EMI) analysis. Lead zirconate titanate (PZT)-5A was identified as a smart material for the SHM application. A flexible high temperature bonding layer was used to address challenge in PZT integration due to significant difference in coefficients of thermal expansion of PZT and the aluminum substrate. The steel joint made on steel core was investigated because it is responsible for ultimate tensile strength of the connector. Tensile testing was used to create structural damage to the joint or steel core pullout while thermal cycling was used to introduce additional structural perturbations. EMI measurements were conducted between the tests. Root mean square deviation (RMSD) of EMI was identified as a damage index. It has been demonstrated that use of steel joints enables the SHM to be developed under simulated conditions. The EMI signature is sensitive to variations in structural conditions. RMSD can be correlated to the structural health of a connector and has potential for use in the SHM and structural integrity evaluation.

10169-22, Session 6

Nondestructive evaluation techniques for thick concrete structures

Dwight A. Clayton, Oak Ridge National Lab. (United States)

The use of concrete structures has made its long-term performance crucial for the safe operation of commercial nuclear power plants (NPPs), especially with license period extensions to sixty years and possibly beyond. Unlike most metallic materials, reinforced concrete used in NPPs is a heterogeneous material, a composite with a low-density matrix, a mixture of cement, sand, aggregate and water, and a high-density reinforcement, made up of steel rebar or tendons. This structural complexity makes nondestructive evaluation (NDE) a challenging task. While the standard Synthetic Aperture Focusing Technique (SAFT) is adequate for many defects with shallow concrete cover, some defects that are located under deep concrete cover are not easily identified using the standard SAFT techniques. For many degradation mechanisms, particularly defects under deep cover, the use of advanced signal processing techniques is required. A variety of test specimens were evaluated using several advanced signal processing techniques ranging from a large specimen representative of a NPP containment wall (2.134 m x 2.134 m x 1.016 m) with twenty embedded defects, specimens with accelerated alkali-silica reaction (ASR), and specimens with freeze-thaw damage. The first technique examined in this paper generates frequency banded SAFT reconstructions using wavelet packet decomposition and reconstruction. While the frequency banded SAFT reconstructions show a vast improvement over the standard SAFT for defects under deep cover, a second technique, Model Based Iterative Reconstruction (MBIR), has been initiated to address the limitations of the frequency banded SAFT (such as multiple reflections for a single defect).

10169-23, Session 6

Understanding the thermal sciences in the electron beam melting process through in-situ process monitoring

Michael Kirka, Oak Ridge National Lab. (United States); Jacob Raplee, Tennessee State Univ. (United States); Alex Plotkowski, The Univ. of Tennessee (United States); Ralph B. Dinwiddie, Ryan R. Dehoff, Oak Ridge National Lab. (United States); Sudarsanam babu, The Univ. of Tennessee (United States)

Additive Manufacturing provides the opportunity to fabricate components of nearly limitless complexity compared to that of traditional manufacturing techniques. However, thermal gyrations imparted into the material from the passing of the heat source cause challenges in fabricating complex structures with the proper process parameters. While the thermal history of the material can be simulated, validating the simulations requires access to thermal data generated as a result of in-situ process monitoring. While generation of in-situ thermal data seems trivial, acquiring and developing reliable calibrations for metallic materials is difficult due to the physical state of the material transitioning from powder to liquid to a solid. To be discussed is the methodology taken to integrate IR in-situ process monitoring within the electron beam melting process and the approach developed to accurately correlate a materials emissivity to temperature during the build process. Further the wealth of information contained within the thermal data will be discussed in the context of understanding of microstructural evolutions within the material during the build process, identification of material defects, and ability to determining the similarity/repeatability of builds fabricated with identical processing parameters as based only on the thermal signature of the build.

10169-24, Session 6

A residual stress study of cast aluminum alloy cylinder heads

Thomas Watkins, Ke An, Amit Shyam, J. Allen Haynes, Oak Ridge National Lab. (United States)

In an effort to increase the fuel efficiency of automobiles, the operating pressures and temperatures must increase, necessitating the need for new aluminum alloys with improved performance at these new extremes. New alloys will result in different residual stress distributions, which could impact castability and durability in service. In this regard, the residual stresses were determined at key locations within cylinder heads cast from baseline and higher temperature alloys using neutron diffraction and compared. Each head was cast from an alloy from the Al-Cu, Al-Si-Cu or Al-Si system. This study is part of a larger study for higher temperature capable cast aluminum alloys.

10169-25, Session 6

High energy x-ray 3D tomography for graphite morphology characterization in cast irons for engine application

Dileep Singh, Chihpin Chuang, John Hryn, Jonathan D. Almer, Peter Kenesei, Argonne National Lab. (United States); Richard Huff, Caterpillar Inc. (United States)

For heavy duty vehicle engine application, development of cast irons with improved mechanical (fatigue, strength) properties is desired for enhanced performance, and consequently, potential for light-weighting. Properties (mechanical, thermal, castability) of cast irons are strongly dependent on the graphite content, 3D morphology, and their spatial arrangement within the material.

The development of high energy x-ray tomography in recent decades makes it a promising technique that provides a comprehensive description of the graphite morphology in the specimen. In this study, we used x-ray tomography technique to perform 3D-characterization of graphite morphologies in different types of mixed graphite (spheroidal and compacted) cast irons. The spheroidal graphite (SG) in alloy-A shows a bi-modal distribution which suggests a two-step nucleation process during solidification. The average diameter of SG in alloy-A is 12 um (large) and 6 um (small), respectively. As for alloy-B, SGs exhibit a tri-modal distribution with an average diameter of ~ 40 um, 14 um and 5 um. The size distribution of SG shows the complex nature of the graphite nucleation during the solidification of cast iron and the sensitivity of post-inoculant species to the graphite morphology. Further, tomography delineates the 3D morphologies of the compacted graphite structures as well. High energy 3D tomography technique can rapidly characterize internal structures, in a statistically meaningful manner, that can be correlated to processing and properties of the cast irons.

10169-26, Session 6

Ultrasonic signatures corresponding to defect localization and onset of instabilities in granular media and lattice structures

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Recently, due to advent of new experimental capabilities and sensing technologies, there has been a renewed interest in wave propagation in granular systems, lumped parameter systems, and lattice structures. These structural systems possess several interesting and tailorable properties that make them a cost-effective choice for a variety of applications in vibration-isolation and sensing. In this paper, we study wave propagation in non-linear periodic media using computer simulations. Important features of non-linear wave propagation like higher harmonic generation, amplitude-dependent wave speeds and their dispersive characteristics are studied based on experimentally motivated non-linear models such as Hertz contact, bifurcation/chaotic non-linear spring models, and non-linear dissipation models. Representative examples are presented to demonstrate the utility of computer simulations for identifying key signatures pertaining to onset of material/structural instabilities and damage localization in granular chains and periodic lattice structures.

10169-27, Session 7

Structural health monitoring with inverse resonance inspection

Xin Sun, Kevin C. Lai, Pacific Northwest National Lab. (United States)

To evaluate a structural component's fitness for service and quantify its remaining useful life, aging and service-induced structural flaws must be quantitatively determined in service or during scheduled maintenance shutdowns. Resonance inspection (RI), a non-destructive evaluation (NDE) technique, distinguishes the anomalous parts from the good parts based on changes in natural frequency spectra. Known for its numerous advantages, e.g., low inspection cost, high testing speed, and broad applicability to complex structures, RI has been widely used for quality inspection of lightweight metal castings. However, compared to other contemporary direct visualization-based NDE methods, a more widespread application of RI faces a fundamental challenge because such technology is unable to quantify the flaw details, e.g., location, dimensions, and types. In this presentation, we review the progresses made in inverse RI algorithm for the identification of the locations, type and severity of various structural flaws. We demonstrate that a variety of common structural flaws, e.g., stiffness degradation, voids, and cracks, can be accurately pinpointed by this algorithm even when multiple different types of flaws coexist. The quantitative relations between the damage identification results and the flaw characteristics can be used to assist in the evaluation of the engineering structures' actual states of health.

10169-28, Session 7

A comparison of different NDE signal proccessing techniques based on waveform entropies applied to long fiber graphite/epoxy plates having near surface defects

Michael Larche, Mathew Prowant, Paul Bruillard, Tobias Hagge, Leonard S. Fifield, Michael Hughes, Xin Sun, Pacific Northwest National Lab. (United States)

This study compares different approaches for imaging of six different type of near-surface defects in thin graphite/epoxy plates using backscattered ultrasound. Five of the defects were 3.81 cm circular foreign object inclusions representing materials sometimes incorporated into graphite/epoxy layups by mistake: 5 mil mylar, teflon, nylon polyethylene, fiberglass sheets. Data were also acquired from a resin-rich region produced by removing a 3.81 cm circular region from the second ply in the layup prior to curing. All specimens were C-scanned on a 100x100 point grid (where delta x and delta y=7.62 mm). At each point on the grid, the 256 backscattered waveforms were digitized into eight-bit, 512 word records that were averaged, then stored on a computer for off-line analysis. The same backscattered waveforms were used to produce peak-to-peak, Signal Energy, as well as entropy images of different types (Shannon, Renyi with weight 1.5, Singular Renyi and Joint Entropies). All of the entropy images exhibit better border delineation and defect contrast (up to a 20-fold increase in some cases) than the either peak-to-peak or Signal Energy. The best results are obtained using the joint entropy of the backscattered waveforms with a reference function. Two different references were examined: a reflection of the insonifying pulse from a stainless steel reflector, and a theoretically "optimum" reference[1]. The joint entropy images produced using this reference exhibit three times the contrast obtained in previous studies. The optimality criterion will be described and the derivation of the optimum reference within this framework will be sketched.

References:

[1]M. Hughes, J. McCarthy, P. Bruillard, J. Marsh, and S. Wickline, ``Entropic vs. energy waveform processing: A comparison based on the heat equation,'' Entropy 17(6), 3518-3551 (2015).

10169-29, Session 7

Non-destructive evaluation of polyolefin thermal aging using infrared spectroscopy

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Near the surface of polymer composites. FTIR can be used to verify composite composition, identify chemical contaminants and expose composite moisture content. Polymer matrix changes due to thermal exposure including loss of additives, chain scission, oxidation and changes in crystallinity may also be determined using FTIR spectra. Portable handheld instruments using non-contact reflectance or surface contact attenuated total reflectance (ATR) may be used for non-destructive evaluation (NDE) of thermal aging in polymer and composite materials of in-service components. We report the use of ATR FTIR to track oxidative thermal aging in ethylene-propylene rubber and cross-linked polyethylene materials used in medium voltage and low voltage nuclear power plant electrical cable insulations. Property changes of these materials with thermal degradation for correlation with FTIR data is tracked using a variety of methods including tensile and indenter mechanical testing, differential scanning calorimetry, density and mass loss measurements. Tensile elongation-at-break (EAB) is often used as a metric of cable insulation health, with decrease of EAB to levels below half of the initial value representing transition of cable toward end of useful service life. The FTIR-determined carbonyl index was found to be proportional to loss in EAB performance and may be a valuable NDE technique for assessing cable remaining useful life.

10169-30, Session 7

Nondestructive evaluation of composite materials via scanning laser ultrasound spectroscopy

Elise Anne Koskelo, Eric B. Flynn, Los Alamos National Lab. (United States)

Composite materials pose a complex problem for ultrasonic nondestructive evaluation due to their unique material properties such as greater damping and greater stiffness. In this study, we explored acoustic wavenumber spectroscopy (AWS) as a new means of rapid inspection of aerospace and honeycomb-celled composites. Using steady-state excitation for a range of ultrasonic frequencies, we excited each aerospace sample using a piezo electric actuator and measured the velocity response of the composite at each pixel via a raster scan using a laser Doppler vibrometer. We were able to detect radial inserts along the corners of two-plane samples as well as areas of delamination by analyzing local amplitude and wavenumber responses. We probed each honeycomb-celled sample using AWS by exciting the sample at its first resonant frequency. The local mode shape for each cell was extracted from the local amplitude response. Analyzing local amplitude and phase responses for each cell provided an accurate indication as to the presence, size, shape, and type of defect present in the composite. We detected both delamination and deformation of cells within a honeycomb composite.

10169-31, Session 8

External monitoring of pressure and dimension changes for energy materials and systems

Gao Liu, Lawrence Berkeley National Lab. (United States)

Most of the energy materials experience significant volume and strain-stress changes during their operational lifetime, which are major sources of the materials and system failures. The external monitoring and analysis of the macroscopic system performance can be related to the micro- or nano-scale material performance and failure in the materials level. The stress changes in the macroscopic level can be real-time monitored using non-destructive strain gauges to correlated with the materials level behavior. We recently developed in depth understanding of the bulk volume change of lithium-ion electrochemical cell with the micro-scale irreversible volume change in the materials level. This irreversible materials level volume change is caused by the materials failure in the nano-scale, which leads to the cell system failure after many long cycles of operations. We will discuss the recent progress in those areas and its further application in the energy materials fields.

10169-32, Session 8

Synchrotron based non-destructive characterization of the dissimilar joints

Wanli Yang, Gao Liu, Lawrence Berkeley National Lab. (United States)

The welding and joining of the dissimilar materials are a challenging issue in the advance materials area. However, the employment of various materials with distinct physicochemical properties in the automotive and aerospace industries has opened a new field of research into the joining of dissimilar materials. Various methods have recently developed for joining

metal-polymer multi-material structures. However, at the very interface of the dissimilar materials, molecular level interactions are the determine force of bulk adhesion, and the mechanical strength of the joint materials. Non-destructive observation of the bonding properties at interface along with bulk scale mechanical properties study can lead to the molecular-level understanding of the bonding interface, which will aid the design of ultra strong adhesive materials for automotive and aerospace applications. Synchrotron based Soft X-ray Spectroscopy is uniquely suitable for this purpose. We have demonstrated that the X-ray Absorption Spectroscopy can be used to clearly differentiate bonding arrangement of diamondoids carbon nano-molecules on the metal surface. The different arrangements have led to unique physical properties of the composite joint. This presentation will discuss the application of soft X-ray spectroscopy as a non-destructive probe of the interface between carbon molecules and metal substrate.

10169-33, Session 8

Combinatorial materials approach to accelerate materials discovery for transportation

Wei Tong, Lawrence Berkeley National Lab. (United States)

Combinatorial material research offers fast and efficient solutions to identify promising and advanced materials. It has revolutionized the pharmaceutical industry and now is being applied to accelerate the discovery of other new compounds, e.g. superconductors, luminescent materials, catalysts etc. Differing from the traditional trial-and-error process, this approach allows for the synthesis of a large number of compositionally diverse compounds by varying the combinations of the components and adjusting the ratios. It largely reduces the cost of single-sample synthesis/characterization, along with the turnaround time in the material discovery process, therefore, could dramatically change the existing paradigm for discovering and commercializing new materials. This talk outlines the use of combinatorial materials approach in the material discovery in transportation sector. It covers the general introduction to the combinatorial material concept, state of art for its application in energy-related research. At the end, LBNL capabilities in combinatorial materials synthesis and high throughput characterization that are applicable for material discovery research will be highlighted.

10169-34, Session 8

Combining density functional theory calculations, supercomputing, and data-driven methods to design new materials

Anubhav Jain, Lawrence Berkeley National Lab. (United States)

Density functional theory (DFT) simulations solve for the electronic structure of materials starting from the Schrödinger equation. Many case studies have now demonstrated that researchers can often use DFT to design new compounds in the computer (e.g., for batteries, catalysts, and hydrogen storage) before synthesis and characterization in the lab. In this talk, I will focus on how DFT calculations can be executed on large supercomputing resources in order to generate very large data sets on new materials for functional applications. First, I will briefly describe the Materials Project, an effort at LBNL that has virtually characterized over 60,000 materials using DFT and has shared the results with over 17,000 registered users. Next, I will talk about how such data can help discover new materials, describing how preliminary computational screening led to the identification and confirmation of a new family of bulk AMX2 thermoelectric compounds with measured zT reaching 0.8. I will outline future plans for how such data-driven methods can be used to better understand the factors that control thermoelectric behavior, e.g., for the rational design of electronic band structures, in ways that are different from conventional approaches.

10169-44, Session PMon

Damage identification in highway bridges using distribution factors

Michael V. Gangone, The Univ. of Texas at Tyler (United States)

The U.S. infrastructure system is well behind the needs of the 21st century and in dire need of improvements. The American Society of Civil Engineers (ASCE) graded America's Infrastructure as a "D+" in its recent 2013 Report Card. Bridges are a major component of the infrastructure system and were awarded a "C+". Nearly 25 percent of the nation's bridges are categorized as deficient by the Federal Highway Administration (FWHA). Most bridges were designed with an expected service life of roughly 50 years and today the average age of a bridge is 42 years. Finding alternative methods of condition assessment which captures the true performance of the bridge is of high importance. This paper discusses the monitoring of two multi-girder/stringer bridges at different ages of service life. Normal strain measurements were used to calculate the load distribution factor at the midspan of the bridge under controlled loading conditions. Controlled progressive damage was implemented to one of the superstructures to determine if the damage could be detected using the distribution factor. An uncertainty analysis, based on the accuracy and precision of the normal strain measurement, was undertaken to determine how effective it is to use the distribution factor measurement as a damage indicator. The analysis indicates that this load testing parameter may be an effective measure for detecting damage.

10169-91, Session PMon

Feasible of optical infrared thermography test for heat shrinkable tapes inspection used in oil and gas pipeline

Yue Yu, China Special Equipment Inspection and Research Institute (China)

Pipeline is the main pathway for oil long-distance transmission. PE heat-shrinkable tape sticking to the pipe is usually used in the field coating of welded joints in China, in the process of its manufacturing and maintenance. Failure of field coating of welded joints because of bonding problem can lead to corrosion, which important common damage of pipeline.Rapid detection technology for heat-shrinkable tape bonding quality is the foundation of pipeline quality control. Nonetheless, finding a effective inspection technology for heat-shrinkable tape bonding quality is a challenging task. In this study, we work on the utilization of optical infrared thermography test for heat-shrinkable tape bonding quality evaluation. A uniform heating infrared lamp is used for the surface heating, thermal detector records the change of the surface temperature. This technology provides a rapid bonding quality testing and assessment technology. The successes and limitations of this technique will be discussed in this article.

10169-92, Session PMon

The mathematical model that describes the periodic spouting of a geyser induced by boiling

Hiroyuki Kagami, Fujita Health Univ. (Japan)

We have derived and modified the dynamical model of a geyser induced by gas inflow and regular or irregular spouting dynamics of geysers induced by gas inflow has been reproduced by the model.

On the other hand, though we have derived the dynamical model of a geyser induced by boiling, periodic change between the spouting period and the pause period has not been adequately modeled by the model.

In this connection, concerning a geyser induced by gas inflow we have

proposed the model as described below. Because pressure in the spouting tube decreases obeying to the Bernoulli's theorem when the spouting period begins and water in the spouting tube begins to flow, inflow of groundwater into the spouting tube occurs. When the amount of this inflow reaches a certain amount, the spouting period transforms to the pause period.

In this study, by applying this idea to the dynamical model of a geyser induced by boiling, the periodic change between the spouting period and the pause period could be reappeared. As a result, the whole picture of the spouting mechanism of a geyser induced by boiling became clear.

This research results would give hints on engineering repair in order to prevent the weakening or the depletion of the geyser. And this study would be also useful for protection of geysers as tourism and environmental resources.

10169-93, Session PMon

An extended Preisach model for effects of magnetization history on magnetomechanical behavior of steel cables

Lin Liu, Chunyuan Li, Rui Li, Yongfu Li, Chongqing Univ. of Posts and Telecommunications (China)

Magnetization history has been known as an essential factor for elaborating magnetomechanical behaviors, which has a direct and great influence on measurement accuracy of magnetic stress monitoring for steel cables. It is therefore desirable to find a method to predict the behavior under differnent processes of magnetization history. This paper proposes an extended Preisach model in which the combination of magnetic field and mechanical stress are treated as an effective field. Preisach diagram of this model is used to qualitatively analyze magnetomechanical behaviors for any kinds of magnetization history based on the characteristic that it is a convenient way of depicting the processes and turning points involved in magnetic history. Magnetomechanical behaviors under a certain kind of magnetization history are discussed with this model. The corresponding experiment is carried out. The results show that it is helpful in forecasting the trend of magnetomechanical behavior affected by the processes and turning points involved in magnetic history, which gives a reasonable understanding of the various magnetomechanical behaviors that, as reported by different researchers, appeared to be contradictory. Moreover, it is useful in improving the measurement accuracy by determining the magnetic condition in magnetic stress monitoring.

10169-96, Session PMon

Application of interface waves for near surface damage detection in hybrid structures

Mohammadreza Jahanbin, Villanova Univ. (United States) and The Boeing Co. (United States); Sridhar Santhanam, Villanova Univ. (United States); Richard H. Bossi, Mark Jahanbin, The Boeing Co. (United States)

Surface bonded waves are ideal for investigating the health of bonded structures because they propagate on the bondline and damage can produce distortion in the path of traveling waves. In past work (Ref), we studied the disbond crack detection capability of interface waves. However, frequently the damage in bonded structures is not exactly on the bondline but lies very close to the interface in the first few plies of the composite. For example in metal-composite hybrid structures, if the strength of the bondline is higher than the bearing strength of the composite, interlaminar delamination can occur due to out of plane and buckling load application.

In this work we study the capability of surface and interface waves for sub surface delamination detection in the composite layers. The acoustic energy of surface and interface waves attenuates and the amplitude decays exponentially with depth into the composite layers. Our study shows the surface and interface waves are still effective to detect near boundary damages in the distance close to one wavelength.

A finite element model has been constructed for bonded aluminum–composite hybrid structure shown in Figure 1. The simulation results show that the delamination in the composite layer affects the time of flight or velocity of interface wave. The time of flight increases as the size (length) of the delamination increases. The depth of the delamination layer does affect the time of flight, decreasing it somewhat relative to delaminations near the interface.

The result of this numerical study can be used for the design of experiments to demonstrate this application of surface and interface waves. The changes in velocity of these waves can be used to locate and size interface and sub-surface damages. Rayleigh wave velocity is slower than Stoneley wave velocity and the Stoneley wave velocity is slower than shear wave velocity in the denser media of hybrid structure. The changes in wave velocities, based on the time of flight, for various delamination damage lengths along the bondline and depths below the bondline are demonstrated in this research study.

10169-97, Session PMon

Guided wave propagation and quantitative evaluation of seawater ingress in GFRP naval composites

Mohit Garg, Shruti Sharma, Sandeep K. Sharma, Rajeev Mehta, Thapar Univ. (India)

In the present study, the authors quantify the influence of water ingress on the diffusion behavior, mechanical properties and non-destructive ultrasonic signal strength due to material degradation as a result of hygrothermal aging in the GFRP composites.

GFRP specimens submerged in seawater (SW) revealed an increasing trend of weight gain versus immersion time. Subsequently, the strength of the material in general tends to decrease as water infusion increases. For example, a reduction of 48% in strain and 66% in the tensile strength was observed after a period of 60 days immersion in SW conditions. The overall degradation in the properties are mainly due to plasticization effect, swelling of the matrix and loss of interfacial bonding between the glass fibers and the matrix when conditioned for long time.

Further, an attempt has been made to investigate the effect of hygrothermal aging on ultrasonic voltage amplitude signals. From the signatures acquired at varying days of hygrothermal loads, it is observed that the signal attenuates rapidly with increasing exposure time. Additionally, the drop in signal strength correlates well with fall in tensile strength with increasing time of immersion for GFRP laminates.

Thus, these experimental findings can go a long way in non-destructive evaluation of GFRP laminates when subjected to hygrothermal loading. The proposed active, non-contact, non-invasive health monitoring technique can serve as an effective method to diagnose the service life of marine vessels while they are in operational mode.

10169-98, Session PMon

Research on multi-parameter monitoring of steel frame shaking-table test using smartphone

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The numerical simulation promises an effective method to assess seismic damage of high-rise structure. But it's difficult to determine the input parameters and the simulation results are not completely consistent with the real condition. A more direct approach to evaluate the seismic damage is the structural health monitoring (SHM), which is one complex set of various kinds of sensors, devices and software, and always needs professionals. SHM system has achieved great development over recent years, especially on bridge structures. However it's not so popular on high-rise building due to its difficult implementation. Developing a low-cost and convenient monitoring technique will be helpful for the safety maintenance of high-rise building. Smartphones, which embedded with sensors, network transmission, data storage and processing system, are evolving towards crowdsourcing. The popularity of smartphones presents opportunities for implementation of portable SHM system on buildings. In this paper, multi-parameter monitoring of a three-storey steel frame on shaking table under earthquake excitations is conducted with smartphone, and the comparison between smartphone and traditional sensors was provided. First, the monitoring applications on iOS platform, Orion-CC and D-viewer, are introduced. then the experiment detail are presented, including three-story frame model, sensors placement, data acquisition system and so on. Third, different earthquake excitations exert on the frame, meanwhile multi-parameters involving acceleration, angle and inter-storey displacement of each story are recorded by smartphone and traditional sensors. Last, the acceleration and displacement time-history curves of smartphone and traditional sensors are provided and compared. The results proved the feasibility of the multi-parameter monitoring of building by using smartphone under earthquake excitations. This method is so simple to operate and the multiple parameters can be obtained to evaluate the seismic damage.

10169-99, Session PMon

Side-drilled hole detection of CFRP without pre-knowledge of anisotropic group velocity

Yongsheng Shao, Jing Lin, Liang Zeng, Xuwei Cao, Xi'an Jiaotong Univ. (China)

Ultrasonic phased array has been widely used for the nondestructive detection of carbon fiber-reinforced plastic (CFRP). The accurate anisotropic group velocity must be obtained beforehand for the detection imaging. It's a great challenge because of the anisotropy of CFRP. In this paper, a novel method is presented for the Side-Drilled Hole (SDH) detection in CFRP, in which the pre-knowledge of anisotropic group velocity is not needed. To begin with, the detection signal of CFRP with SDH was gained by the mode of FMC (full matrix capture). Then a limited angle range of the anisotropic group velocity is obtained by the back-wall reflection method (BRM). The angle range of velocity is extended by matching the delay time of back-wall and SDH reflection and analyzing the relation between the reflection of back-wall and SDH. Although the acquired angle range can't cover all the directions, it's still sufficient to image SDH. Finally, the total focusing method (TFM) is used to image CFRP. Furthermore, the weak defect located between SDH and back-wall may also be detected. An experiment was conducted on a sample of CFRP with SDH. The SDH can be seen clearly in the image.

10169-100, Session PMon

Fault diagnosis of rotating machinery using wavelet-based feature extraction and support vector machine classifier

Han Tran, California Polytechnic State Univ., San Luis Obispo (United States)

In this research, a gearbox damage detection strategy based on discrete wavelet transform (DWT), wavelet packet transform (WPT), support vector machine (SVM), and artificial neural networks (ANN) is presented. Three case studies are conducted to compare the classification performance of SVM kernel functions and ANN. First, a fault detection analysis based on DWT and WPT is carried out to extract the damage information from the gearbox's raw vibration signal. In this step, wavelet coefficients obtained from DWT are characterized using statistical calculations. Energy characteristics of the gearbox signal are acquired using WPT and their statistical characteristics are also computed. These three sets of information extracted from wavelet transforms are utilized as the input to SVM and ANN classifiers. Secondly, the improved distance evaluation technique (IDE) is implemented to select the sensitive input features for SVM and ANN. The penalty parameter C and kernel parameter γ in SVM are also optimized using the grid-search method. Finally, the optimized features and parameters are input into SVM and ANN algorithms to detect gearbox damage. The result shows that gearbox damage detection using energy characteristics extracted from WPT (Case 2) or their statistical values as input features (Case 3) to the learning algorithms produces higher classification accuracies than using statistical values of the DWT coefficients as inputs (Case 1). In addition, RBF-SVM has the best classification performance in Case 2 and 3 while Linear-SVM has the best classification accuracy rate in Case 1 in damage detection average.

10169-101, Session PMon

Detection of damage in advanced materials using laser Doppler vibrometry

Theodoti Kordatou, Ilias K. Tragazikis, Theodore E. Matikas, Univ. of Ioannina (Greece)

In recent years, the damage assessment by means of Laser Doppler Vibrometry (LDV) has become very attractive as it provides non-contact, non-destructive, accurate and improved evaluation of advanced materials. This study deals with the development of advanced software based on LabVIEW in order accurate and automated measurements of acoustic activity to be achieved. Furthermore, this automated method was applied for damage detection in Al-SiC Metal Matrix Composites undergone cyclic mechanical loading. LDV was used to measure the amplitude of a Rayleigh surface wave propagating in Al-SiC specimens. Rayleigh waves are experimentally generated with a piezoelectric transducer and detected by LDV. The proposed measurement technique is used to assess the damage and its evolution, in terms of the increasing amplitude of Rayleigh wave, in Al-SiC specimens under cyclic mechanical loading. In addition, the reduction in the Rayleigh wave velocity it depends on ultimate fatigue strength of material. The development of this process allows the automated, improved and detailed damage assessment of composite materials.

10169-102, Session PMon

The effect of erosion on the fatigue limit of advanced composite materials

Evangelos Z. Kordatos, Sheffield Hallam Univ. (United Kingdom); Dimitrios A. Exarchos, Theodore E. Matikas, Univ. of Ioannina (Greece)

This work deals with the study of the fatigue behavior of advanced composite materials which have undergone erosion. Particularly, an innovative non-destructive methodology based on infrared lock-in thermography was applied on metal matrix composite materials (MMCs) for the rapid determination of their fatigue limit. The effect of erosion on the structural integrity of materials can lead to a catastrophic failure and therefore an efficient assessment of the fatigue behavior is of high importance. Infrared thermography (IRT) as a non-destructive, non-contact, real time and full field method can be employed in order the fatigue limit to be rapidly determined. The basic principle of this method is the detection and monitoring of the intrinsically dissipated energy due to the cyclic fatigue loading. This methodology was successfully applied on both eroded and non-eroded MMCs specimens in order the severity of erosion effect to be evaluated.

10169-103, Session PMon

Variable thick plate focus scan imaging detection with a 2D array guided wave transducer

Shiyuan Zhou, Zhe Li, Chunguang Xu, Shaohan Wang, Xuan Wu, Beijing Institute of Technology (China)

Comb array transducer can be used to excite guided waves. By imposing time delay, focused guided wave field can be excited by a 2D array transducer. It's difficult to form a focused guided wave field in a variable thick plate, because guided wave transmission dispersion make the phase velocity and group velocity changing upon different thickness. This paper analyzed the guided waves propagation characteristics for choosing an appropriate non-dispersive mode. With this non-dispersive mode, focused guided wave was achieved through a Mode-Spatial Double Phase Focusing method (MSDPF). Experiments of this focusing method is carried out in a variable thick aluminum plate. Imaging detection of the variable thick aluminum plate is also succeed by focus scanning based on MSDPF method. Crack defect size of 0.1mm ? 5mmcan be clearly discovered. The prospect of applied in on-spot fast-speed imaging detection for variable thick plate member can be expected.

10169-104, Session PMon

A close inspection and vibration sensing aerial robot for steel structures with an EPM-based landing device

Kazuya Takeuchi, Arata Masuda, Shunsuke Akahori, Yoshiyuki Higashi, Nanako Miura, Kyoto Institute of Technology (Japan)

This paper presents a development of an aerial robot for the use of close inspection and vibration measurement of a steel structure. It is an urgent problem for advanced countries to maintain the safety of existing infrastructures in a laborsaving and cost-effective manner. An areal inspection robot may potentially be an effective solution for the inspection of the infrastructure like a bridge, but its vulnerability to the wind disturbance and the risk of the collision to the target structure are the critical issues for the close inspection. In this study, we propose an aerial robot which has a landing device consisting of three electro-permanent magnets (EPMs) which allows the robot to land on/ take off the surface of steel structures. Thanks to the landing device, the robot can conduct close image inspection in a stable position. Furthermore, by exploiting the advantage of the landing device, we propose to use the robot as a mobile sensor node for vibration-based structural health monitoring. To this end, a vibration sensor (accelerometer) is installed on the body of the robot. The paper mainly focus on the performance of the vibration measurement by the robot, stably attached to the structure, and its improvement using an inversion filter to eliminate the influence of the robot dynamics on the measurement quality. Experimental studies using the arial robot and a model structure are conducted to examine the validity of the proposed concept.

10169-105, Session PMon

Nondestructive spectroscopic characterization of building materials

Aschalew Kassu, Carlton W. Farley III, Jonathan Mills, Lauren Walker, Rachel Sanders, Anup Sharma, Alabama A&M Univ. (United States)

The purpose of this research project is to use Raman spectroscopy technique to identify the distinct characteristics of construction materials. The results reported include the spectroscopic characterization of building materials using compact Raman system with 785 nm wavelength laser. The construction materials studied include polyblend sanded grout, fire barrier sealant and white silicone. It is found that, fire barrier sealant has a prominent Raman peak at 1082 cm-1, and three minor Raman signatures located at 275, 706 and 1436 cm-1. On the other hand, sand grout has three major Raman bands at 1265, 1368 and 1455 cm-1, and four minor peaks at 1573, 1683, 1762, and 1868 cm-1. White silicone, which is a widely used sealant material in construction industry, has two major Raman bands at 482 and 703 cm-1, and minor Raman characteristic bands at 783 and 1409 cm-1.

10169-106, Session PMon

Structural model updating of small damages using response surface method

Linren Zhou, Huang Song, Bo Wu, South China Univ. of Technology (China)

Structural model updating of small and local damages using structural global responses is full of challenges. Updating a finite element model of a large and complex structure involves a large number of updating parameters and these parameters have obviously different sensitivity to structural measurements. In the model updating, the parameter with large sensitivity converge quickly and parameter with small sensitivity cannot be effectively corrected. In this study, a improved response surface (RS) method is proposed to solve this problem. Firstly, the sensitivity of each parameter to structural measurements is calculated, and the parameters are classified into two or three groups according to the sensitivities. Then, the central composite design (CCD) is used for sampling, and adjusting the CCD samples of each parameter group result in all of the parameters do not have much difference in sensitivities to the measurements. A response surface model is established based on the new samples and model updating is implemented. At last, the updated results are recalculated to the actual situation using inverse operators. A numerical simulation based on a space truss model is carried out to verify the feasibility and effectiveness of this method.

10169-107, Session PMon

On impedance measurement of reinforced concrete on the surface for estimate of corroded rebar

Akira Sasamoto, Jun Yu, Yoshihisa Harada, National Institute of Advanced Industrial Science and Technology (Japan); Masahiro Iwata, Kazuhiro Noguchi, EMIC (Japan)

In estimate of health monitoring for reinforced concrete, corrosion degree of rebar is important parameter but is not easy to be estimated by non destructive testing. A few test method such as half cell method and polarization resistance method could be a 'perfect' nondestructive method if luckily having had wired connection to rebar without destructing target concrete.

In this presentation it is reported that several measurements of impedance on surface of reinforced concretes with different corrosion degree show the validity to distinguish concrete with corroded rebar from one with healthy rebar. The contact electrode on concrete surface are simple structure made of sponge and needle. Impedance measurement are carried out by impedance analyzer with its frequency range from 0.01Hz to 1MHz, typical imposed voltage are 10 volt.

We made concrete specimen under two different corrosion process, One group are corroded by electrolysis before concrete casting (pre corrosion) and another group have corrosion progressed during cure process (post corrosion).

The result of applying the method to these two kind of corroded specimen show that this measurement is valid to estimate corrosion.

10169-108, Session PMon

Phase sensitive thermography for quality assessment of giant magnetostrictive composite materials

Peng Yang, Rani F. Elhajjar, Chiu-Tai Law, Univ. of Wisconsin-Milwaukee (United States)

Giant magnetostrictive materials are increasingly proposed for smart material applications such as in sensors, actuators, and energy harvesting applications. In a composites form, the materials are combined in particle form with polymer matrix composites. Reviewing the literature on this topic, the reader observes a large amount of variability in the reported properties that are typically generated from far-field magnetic measurements and/or overall strain or point-value strain measurements using strain gages. The ability to understand how the microstructure in magnetostrictive composite's results in spatial variability of the localized magnetostrictive response has been an area that has previously not received significant attention. In this paper, a full-field phase-sensitive thermography method is proposed to relate the full-field infrared measurements to changes in the microstructure in magnetostrictive polymer composites when a cyclic magnetic field is applied. The results show how geometry and defects in the material can be rapidly identified from the phase sensitive thermography approach in inspecting the manufactured smart composites.

10169-109, Session PMon

Monitoring applied stress and creep effects in concrete using ultrasonic full-waveform comparison techniques

Ali Hafiz, Thomas Schumacher, Portland State Univ. (United States)

Ultrasonic testing is a non-destructive approach commonly used to evaluate concrete structures. A challenge with concrete is that it is heterogeneous, which causes multiple scattering resulting in longer and more complex wave paths. In this study we present an active monitoring approach employing a pitch-catch setup with two ultrasonic transducers, one transmitter and one receiver, that were attached to Ø 152 x 305 mm concrete cylinder specimens. The transmitted wave was a 100 kHz Morlet-type signal. The received acoustic wave signal can be divided into two portions: the coherent (or early) and the diffuse (or Coda) portion. While conventional methods only use the coherent portion, e.g. to determine the wave velocity, we are interested in the entire waveform, i.e. until the signal is completely dampened out. The objective of our study was to determine what portion of the signal is most sensitive to applied stress, the formation of associated micro-cracks, and resulting creep. The experimental tests consisted of subjecting the specimens to an increasing uniaxial compression load. Using digital signal processing, two comparison metrics were explored and are discussed in this paper: linear correlation and magnitude-squared coherence. Both produce measures of the correlation (or similarity) between a reference signal under no stress and a signal taken at a certain level of applied stress. Our results show that applied stress correlates well with these two metrics with remarkable sensitivity to small stresses. Additionally, they also show promise for their ability to estimate residual stresses.

10169-110, Session PMon

Performance evaluation of guidance and control system on hypersonic vehicle

Megnran Li, Yongji Wang, Lei Liu, Huazhong Univ. of Science and Technology (China)

In this paper, a set of performance evaluation framework on hypersonic vehicle has been proposed. Now guidance/control law (GCL)design has been very mature, but related literature on how to evaluate the GCL is scattered . And there is little literature introducing how to evaluate different GCLs. So this paper forms an assessment framework,and in this framework,analyzing the performance from only one GCL to different GCLs is described.And to evaluate the flight's integrated performance comprehensively, and to consider the flight's robustness,orthogonal experiment method is adopted,because of that many factors have to be considered, such as wind interference, atmospheric density variations, aerodynamic coefficient deviations,so on and so forth. So we can select a suitable orthogonal table to get different factors combination instead of all factors' arrange and combination. Utility function is used to normalize the different indexes to remove the difference caused by the different units and some functions is used to get the corresponding scores. Analytic Hierarchy Process(AHP) is used to calculate the index's weight. To evaluate different GCLs and sort the GCLs according to their performance, the angle of objective weighting method is used to calculate the weight of different factor combination.And then Technique for Order Preference by Similarity to an Ideal Solution(TOPSIS) is used to sort different GCLs according to their performance. TOPSIS considers the GCLs' performance comprehensively and then makes an arrange. Finally the results show that these methods are useful to performance evaluation.

10169-35, Session 9

Cable fracture detection with acoustic emission

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In this study, acoustic emission (AE) tests were conducted to detect and locate wire fracture in strands that are widely used in cable-stayed and suspension bridges. To effectively separate fracture signals from unwanted noises, distinct features of fracture, fracture-induced echo, and artificial tapping signals as well as their dependence on loading levels are characterized with short-time Fourier transform. To associate fracture scenarios with their acoustic features, two 20-foot-long (~6.1 m) 270 ksi (~1,862 MPa) steel strands of seven wires were tested with one wire notched off at center and support, respectively, up to 90% of its cross section area by 10% increment. Up to 80% reduction in cross section area of the notched wire, each strand was loaded to 20 kips (~89 kN) corresponding to 35% of the minimum breaking strength and the acquired AE parameters such as hits, energy, and counts were found to change little. With a reduction of 90% of the section area of one wire, both strands were found to be fractured under approximately 16.5 kips (~73.4 kN). The hits, energy, and counts of AE signals were all demonstrated to suddenly change with the fracture of the notched wire. However, only the counts of AE signals distributed over the length of the strands allow the localization of fracture point. The frequency band of fracture signals is significantly broader than that of either fracture-induced echo or artificial tapping noise. The time duration of artificial tapping noises is substantially longer than that of either fracture or fracture-induced echo. These distinct characteristics can be used to effectively separate fracture signals from noises for wire fracture detection and localization in practice.

10169-36, Session 9

Finite element model updating of multi-span steel-arch-steel-girder bridges based on ambient vibrations

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The three-span steel-arch-steel-girder Jiaxian Bridge was newly constructed in 2010 to replace the former one that has been destroyed by Typhoon

Sinlaku (2008, Taiwan). It was designed and built to continue the domestic service requirement, as well as to improve the tourism business of the Kaohsiung city government. This study aimed at establishing the baseline model of Jiaxian Bridge for hazardous scenario simulation such as typhoon, flooding and earthquake. Necessities of these precaution works were attributed to the inherent vulnerability of the sites: near fault and cross river. The uncalibrated baseline bridge model was built with structural finite element in accordance with the blueprints. Ambient vibration tasks were performed repeatedly to acquire the elastic dynamic characteristics of the bridge structure. Both frequency and time domain system identification algorithms were employed to extract the measured operational modal parameters. Modal shapes and modal assurance criteria (MAC) were configured as the fitting targets to calibrate the structural parameters of the baseline model. It has been recognized that different types of structural parameters contribute distinguishably to the fitting targets, as this study has explored similarly. For steel-arch-steel-girder bridges in particular this case, joint rigidity of the steel components was found to be dominant while material properties and section geometries relatively minor. The updated model was capable to provide more rational elastic responses of the bridge superstructure under normal service conditions as well as hazardous scenarios.

10169-37, Session 9

Development of linear shear piezoelectric phased array for structural health monitoring

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A novel d36 type piezoelectric wafer which can generate in-plane shear horizontal (SH) waves in the plane-like structures is proposed to assemble and develop a linear phased array for nondestructive testing and structural health monitoring. Rather than the Lamb waves induced by the conventional d31 type piezoelectric wafer, SH waves launched by the d36 type piezoelectric wafer are nondispersive and sensitive to the damage. After the investigation of a single wafer, the directionality and central symmetry of the waves produced by the d36 type piezoelectric are presented. Both the numerical simulation and experimental tests are studied in this paper. Local Interaction Simulation Approach (LISA) method is used to simulate the propagation of waves in the plate. A laser Doppler vibrometer (LDV) is employed to visualize the wave field of the d36 type phased array in an aluminum plate. Experimental results obtained by both the LDV and the passive phased array indicate a great capability of SH waves phased array for damage detection in the structures.

10169-38, Session 9

Development of an integrated lifetime assessment model for bridge condition evaluation

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To effectively conduct bridge management practices, it is critical to accurately understand and estimate the future condition of the bridge inventory. The current established deterioration models severely suffer from the lack of accurate input data. These information include the National Bridge Inventory (NBI) and AASHTO element level ratings periodically collected from bridges, environmental data (e.g., snowfall events, freeze-thaw cycles), traffic data (average daily truck traffic, weigh in motion), geometrical specification (length, skew, etc.). Consequently, the developed deterioration models result in inaccurate prediction of remaining service life, eventually leading to improper maintenance policies and hence significantly inflates agency and user costs. To address this issue, the Federal Highway Administration (FHWA) Long-Term Bridge Performance (LTBP) Program dedicated considerable efforts in developing an unique bridge performance assessment framework. In addition to the historical databases, the detailed Structural Health Monitoring (SHM) and multi-modal Non- Destructive Evaluation (NDT/NDE) testing results are integrated throughout the probabilistic modeling to refine the outcomes. This approach reduces the under/over estimations of the models obtained from imprecise information, resulting in more accurate budgeting and life-cycle cost savings. In essence, the proposed methodology integrates the NDT/NDE results of five techniques (Impact Echo, Electrical Resistivity, Ground Penetrating Radar, Half Cell Potential, Ultra Sound Wave) along with the SHM (Eigen frequencies, mode shapes, vibration intensity) and high resolution visual inspections to accumulate and improve the preliminary bridge condition prediction into a refined condition rating. To verify the robustness of proposed framework, a set of national bridges with detailed NDT/NDE and SHM results are employed in a case study, yielding comparable results.

10169-39, Session 9

An innovative approach in deterioration modelling of bridge using AASHTO element-level condition rating

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The United States bridge network is rapidly deteriorating, while the state department of transportations are in budget limitation. Bridges are critical components keeping the integrity of US highway infrastructure in a well-standing condition. The cornerstone of sound bridge management is to effectively evaluate the condition of bridge components and then, predict the bridge performance in both short and long terms. In the early 1990's, the introduction of element-level inspection technique (or the so called National Bridge Element (NBE)) has significantly empowered the bridge community with a better assessment framework. Primarily, NBE approach determines the overall condition of the bridge on the basis of its individual primary load carrying members, including deck, bearing, joints, wearing surface, etc. This technique is an extension of National Bridge Inventory (NBI)'s approach where only three main components (deck, superstructure, and substructure) are conditionally rated. Since the NBE's initiation, only very few states have collected such information in their bridge inventories resulting in a serious lack of academic investigations. Accordingly, the present study develops an innovative deterioration modeling approach to utilize the NBE historical data in order to forecast the future condition of primary load bearing component. To do so, comprehensive historical NBE information from Oregon state bridges is employed to formulate a probabilistic hazard-based (survival) deterioration model, subsequently implemented for the verification purposes. Proof validations, parametric analysis, as well as sensitivity analysis are further justified the superior performance of the proposed modeling scheme compared to the traditional ones.

10169-40, Session 10

Comparison of electrical impedance tomography inverse solver approaches for distributed strain sensing

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An inkjet-printed carbon nanotube thin film was recently developed to measure strain responses and to detect structural damage. When coupled with electrical impedance tomography (EIT), it can be used as a distributed strain sensor for measuring highly localized strain changes of the underlying structure to which it is attached. In short, EIT is an algorithm that reconstructs the spatial conductivity response of a conductive body using only voltage measurement along its boundaries. Since the thin film's electrical properties are sensitive to strain at every location, mapping the distribution of its conductivity allows one to obtain its corresponding strain distribution. To date, the EIT inverse problem has been solved using different techniques. The objective of this study is to compare the performance of three different approaches. The first technique is based on EIDORS, which is an open-source EIT solver based on the maximum a posteriori (MAP) approach. It can rapidly, using a one-step linear approach, evaluate the relative impedance change of a given region when a baseline measurement (i.e., the response collected under its initial state) is provided. The second approach employs an iterative inverse solver based on a Gauss-Newton method. This approach iterates to minimize the differences in numerical versus experimental boundary voltages (until an acceptable threshold has been reached) to which it then outputs the estimated spatial conductivity distribution of the body. Lastly, a data-driven technique was also implemented. Experiments were conducted to subject the carbon nanotube strain sensor to different strain distributions. Boundary voltage measurements were obtained, and the same sets of data were used as inputs to the three different solvers. The performance (i.e., resolution and accuracy of spatial conductivity estimation) of each solver was evaluated and compared.

10169-41, Session 10

The integration of periodic truss bridge design and impulse response method

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Global structural monitoring strategies for steel truss bridges have the challenges as the influence of boundary conditions on the comparison of predicted and measured properties, and the insensitivity of current methods to small flaws. It is important to consider the damage mechanisms and their influences to structural behavior in the design process. In this paper, the truss optimization is linked with periodic structure design such that each periodic unit (repetitive truss section) has distinct dispersion curve that can be monitored in time for the presence of damage. The numerical model of periodic unit is performed for pristine and cracked conditions. The changes in dispersion behavior with the increase of damage are noted. A section of the truss is built in the laboratory, and the dispersion of periodic unit is obtained using impulse response method in order to reduce the influence of boundary conditions. The changes of dispersion curve of periodic cell with the increase of damage are compared with the numerical results. The proposed design strategy integrates the damage detection philosophy to the design stage, and increases the reliability of nondestructive evaluation method.

10169-42, Session 10

Damage localization and quantification of a pretensioned concrete beam using stochastic subspace identification

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The stochastic subspace identification (SSID) is a system identification technique enabling natural input modal analysis in the time domain. Research in the field of structural health monitoring has demonstrated that SSID can be used successfully to retrieve modal properties, including modal damping, using output-only measurements. In this paper, we investigate the utilization of SSID for indirectly retrieving the stiffness matrix of a simply supported reinforced concrete beam subjected to dynamic loading. The reconstruction is based on the Guyan system condensation concept, which enables calculation of reduced order stiffness, damping, and mass matrices for the structural system. The method computes the reduced order matrices directly from the modal properties, obtained through the use of SSID. Lastly, the reduced properties of the system are used to reconstruct the stiffness matrix of the beam. The proposed approach is first verified through numerical simulated data and then validated using experimental data obtained from a full-scale prestressed, pretensioned concrete beam that experienced progressive to damage.

10169-43, Session 10

Nondestructive testing and monitoring of stiff large-scale structures by measuring 3D coordinates of cardinal points using electronic distance measurements in a trilateration architecture

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By using three, or more, electronic distance measurement (EDM) instruments, such as commercially available laser trackers, in an unconventional trilateration architecture, 3-D coordinates of specialized retroreflector targets attached to cardinal points on a structure can be measured with absolute uncertainty of less than one part-per-million. For example, 3-D coordinates of a structure within a 100 meter cube can be measured within a volume of a 0.1 mm cube (the thickness of a sheet of paper). Relative dynamic movements, such as vibrations at 30 Hz, are typically measured 10 times better, i.e., within a 0.01 mm cube. Measurements of such accuracy open new areas for nondestructive testing and finite element model confirmation of stiff, large-scale structures, such as: buildings, bridges, cranes, boilers, tank cars, nuclear power plant containment buildings, post-tensioned concrete, and the like by measuring the response to applied loads, changes over the life of the structure, or changes following an accident, fire, earthquake, modification, etc. The sensitivity of these measurements makes it possible to measure parameters such as: linearity, hysteresis, creep, symmetry, damping coefficient, and the like. For example, cracks exhibit a highly non-linear response when strains are reversed from compression to tension. Due to the measurements being 3-D, unexpected movements, such as transverse motion produced by an axial load, could give an indication of an anomaly—such as an asymmetric crack or materials property in a beam, delamination of concrete, or other asymmetry due to failures. Details of the specialized retroreflector are included.

10169-46, Session 11

A pre-posterior analysis framework for quantifying the value of seismic monitoring of infrastructure

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Adoption of a monitoring system should be based on sound appraisal of the likely economic benefits of such decisions. These benefits can be quantified

in terms of the reduction of the risks posed by the failure of structural system to be monitored versus the cost of monitoring. Yet, there seems to be dearth of appropriate tools for such decisions. This paper discusses a framework for rationalising the adoption of structural health monitoring for infrastructure, such as buildings, bridges, dams etc., subjected to seismic risk. This is cast in the theoretical rigour of the pre-posterior decision analysis accounting also for the uncertainties in the decision making process. Two types of monitoring are considered, namely for i) a quick appraisal of a single structure's state and damage following a seismic event, and ii) for updating the seismic risk for a single structure or a larger stock of structures through long term monitoring. In the context of quick post-event condition assessment, methods for automatic damage detection and joint utilisation of monitoring and visual inspection data are considered from a point of view of how they can be used in the pre-posterior analysis. Modelling of the various consequences or costs of earthquakes, including damage to structural and non-structural components and content, human fatalities, injuries and trauma, and loss of function are also discussed as an indispensable ingredient of modelling risk. Illustrative numerical examples are included.

10169-47, Session 11

Experimental damage localization in a full-scale 7 story benchmark building under seismic excitation

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In seismic regions Structural Health Monitoring allow performing an objective estimation of the structural damage after a strong motion earthquake. In recent years vibration based damage identification techniques have been widely applied to the assessment of the health state of the buildings. Several researchers have worked to set-up new methodologies for SHM based on the detection of variations, after a strong seismic event, of the structural dynamic characteristics, namely the modal parameter (frequencies, mode shapes, damping) or non-modal parameters like the operational deflection shapes (ODS).

Many of the methods proposed in literature carry out the damage identification through comparison of the original (undamaged) state and the (possibly damaged) current state. The different ways to perform this comparison have led to a number of different. Methods based on frequency changes can be reliably applied to detect damage, but they are hardly able to give information about the location of damage. To this aim are more effective methods based on the analysis of changes of modal or operational shapes and/or of their derivatives such as slopes, curvatures or strain energy. The Modal Interpolation Method (IM), recently proposed, is based on a damage feature defined in terms of the loss of smoothness (that is local increases of curvature) of the modal shapes induced by a local reduction of stiffness. Herein the combination of the IM with the Curvature Evolution Methods is proposed. The CEM is based on the use of a Band-Variable Filter able to extract from recorded responses the nonlinear response of each mode of vibration thus allowing the detection of possible changes occurred during a single earthquake in terms of a damage feature which is defined in terms of the modal curvature. The combination of the two methods CEM and IM is carried out herein using the Band-Variable Filter to extract the non linear response of the structure and assuming as a damage feature the variation of the interpolation error computed at different times during the strong motion.

The combined approach, named Interpolation Evolution Method (IEM) is herein validated by means a full scale experimental benchmark tested on the UCSD-NEES shake table.

10169-48, Session 11

Highly nonlinear solitary waves to estimate the modulus of concrete with different water-to-cement ratios

Amir Nasrollahi, Wen Deng, Piervincenzo Rizzo, Univ. of Pittsburgh (United States)

We describe the feasibility and the reliability of a nondestructive evaluation (NDE) method for concrete. The method is based on the propagation of highly nonlinear solitary waves (HNSWs) along a one-dimensional chain of spherical particles placed in contact with the concrete to be tested. The chain is part of a built-in transducer designed and assembled to excite and detect HNSWs. The method exploits the dynamic interaction between the particles and the concrete. The hypothesis is that the interaction depends on the stiffness of the concrete and influences the time-of-flight and the amplitude of the solitary pulses reflected at the transducer/concrete interface, and traveling within the chain. The results show that the time of flight is monotonically dependent upon the modulus of elasticity of the concrete and that the transducers designed and assembled in this study are reliable and repeatable. In the future, the proposed NDE method may potentially serve as a cost-effective tool for the rapid evaluation of existing concrete structures.

10169-49, Session 11

Accuracy analysis of point cloud modeling for evaluating concrete specimens

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Photogrammetric methods such as structure from motion (SFM) have the capability to acquire accurate information about geometric features, surface cracks, and mechanical properties of specimens and structures in civil engineering. Conventional approaches to verify the accuracy in photogrammetric models usually require the use of other optical techniques such as LiDAR. In this paper, geometric accuracy of photogrammetric modeling is investigated by studying the effects of number of photos, radius of curvature, and point cloud density (PCD) on estimated lengths, areas, volumes, and different stress states of concrete cylinders and panels. Four plain concrete cylinders and two plain concrete panels were manufactured for the study. A commercially available mobile phone camera was used in collecting all photographs. Agisoft PhotoScan software was applied in photogrammetric modeling of all concrete specimens. From our results, it was found that the increase of number of photos does not necessarily improve the geometric accuracy of point cloud models (PCM). It was also found that the effect of radius of curvature is not significant when compared with the ones of number of photos and PCD. A PCD threshold of 15.7194 pts/cm3 is proposed to construct reliable and accurate PCM for condition assessment. At this PCD threshold, all errors for estimating lengths, areas, and volumes were less than 5%. Finally, from the study of mechanical property of a plain concrete cylinder, we have found that the increase of stress level inside the concrete cylinder can be captured by the increase of radial strain in its PCM.

10169-50, Session 11

Quantitative reference-free dynamic distributed sensing of damage

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Monitoring of distributed strains provide important information about

the behavior of structural systems. However, detection and quantification of cracks while still at micro size levels will play a more important role in structural health monitoring. A reference free damage detection method based on distributed monitoring of strains in large structural systems is introduced. The method employs the dynamic distributed strain data to formulate its own virtual reference state for detection of defect locations. It uses a single line of optical fiber by way of Dynamic Pulse-Pre-Pump (Amplitude Transfer) Brillouin Scattering technique in order to acquire dynamic distributed strain data. Further, it is focused on the development of a theoretical approach for establishment of correlation between the crack opening displacements and sensed dynamic distributed strains based on the Brillouin Optical Time Domain Analysis (BOTDA) technique. The correlation relationship is employed for quantification of the crack opening displacements from the measured strains. The strain averaging effect due to the spatial resolution, inherent in Brillouin systems, was also considered in the formulation of the method. The experimental program involved employment of a BOTDA system in the dynamic mode for testing a fifteen-meter length of a steel beam with two fabricated cracks. Experimental results indicated that it is possible to detect and quantify crack opening displacements of 200 microns and larger. The implications of this approach are significant since it enables the structure to be monitored at any stage during its service life without the need for prior reference data.

10169-51, Session 11

Condition assessment of corroded steel rebar in free space using synthetic aperture radar images

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Synthetic aperture radar (SAR) imaging of construction materials offers civil engineers an oppor-tunity to better assess the condition of aging civil infrastructures such as reinforced concrete (RC) structures. Corrosion of steel rebar in RC structures is a major problem responsible for their premature failure and unexpected collapse. In this paper, SAR imaging is applied to the quantita-tive assessment of corroded steel rebar in free space as the first step toward the use of SAR imaging for subsurface sensing of aging RC structures. A 10 GHz stripmap SAR system was used inside an anechoic chamber. The bandwidth of the radar system was 1.5 GHz. Steel rebar specimens were artificially corroded to different levels by regularly applying a mist of 5% NaCl solution for different durations of time in order to simulate the condition of natural corrosion. Two sizes (No. 3 and No. 4) of steel rebar were used in this research. Difference orientations of steel rebar were considered. Corrosion level was determined by measuring the mass loss of corroded steel rebar specimens. From our results, feasibility of SAR images for the condition assessment of corroded steel rebar was experimentally demonstrated. It was found that the presence of surface rust on corroded steel rebar reduces the amplitude in SAR images. The SAR image of corroded steel rebar also exhibited a distribution of SAR amplitudes different from the one of intact steel rebar. In addition, it was also found that there is an optimal range for the condition assessment of corroded steel rebar in free space. In our experiment, the optimal range was determined to be 30.4 cm.

10169-52, Session 11

Continuous and embedded solutions for SHM of concrete structures using changing electrical potential in self-sensing cement-based composites

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Interest in the concept of self-sensing structural materials has grown in recent years due to its potential to enable continuous low-cost monitoring of next-generation smart-structures. The development of cement-based smart sensors appears particularly well suited for monitoring applications due to their numerous possible field applications, their ease of use and long-term stability. Additionally, cement-based sensors offer a unique opportunity for structural health monitoring of civil structures because of their compatibility with new or existing infrastructure. Particularly, the addition of conductive carbon nanofillers into a cementitious matrix provides a self-sensing structural material with piezoresistive characteristics sensitive to deformation. The strain-sensing ability is achieved by correlating the external loads with the variation of specific electrical parameters, such as the electrical resistance or impedance. Selection of the correct electrical parameter for measurement in correlation with specific monitored features is required to progress the concept of cement-based, self-sensing structures. In this paper, we investigate the potential of using altering electrical potential in cement-based materials doped with carbon nanotubes to detect modal frequencies and shapes of concrete structures. Experimental validation is carried out on a small-scale steel reinforced beam of conductive cement paste and a full-scale reinforced concrete beam with embedded carbon nanotube cement-based sensors. Comparisons with constant electrical potential and current methods commonly found in the literature are made. Experimental results demonstrate the ability of the changing electrical potential at detecting features important to civil engineers.

10169-94, Session 11

Study on temperature and damage sensing capability of Portland cement through the thermoelectric measurements

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This study attempted to investigate the self-sensing capability of Portland cement in sensing temperature and detecting damages through the measurements of materials' thermoelectric properties. Specimens were made of Ordinary Portland Cement (OPC) with the water to cement ratio of 0.4. Temperature sensing property was characterized at various ages from 28 to 49 days and at dried/moisturized conditions. It was found there exists a linear relationship between temperature differences and the measured voltages, which is known as the Seebeck effect. This linearity was observed to be varied but able to be characterized for cement pastes at different ages and dried/moisturized conditions. Mechanical loading that introduced different types and degrees of damages also translated into variations of the thermoelectric properties. Different types of compressive loads were tested for comparison. Results have shown that Seebeck coefficient dropped with introduced damages, and restored with the subsequent re-curing as well as the continued hydrating processes. Severe damages would cause significant drop of the coefficient and restrain the restoration. Determination of the damage threshold was not yet revealed in this study, while it is shown obviously there exists one. Our investigation contributed a conclusion that self-sensing capability of cementitious materials is achievable through the measurements of thermoelectric properties. This study, in particular, demonstrated the temperature and damage sensing capability.

10169-53, Session 12A

High temperature transducer using aluminum nitride single crystal for laser ultrasound detection

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Ultrasound nondestructive evaluation (NDE) of materials, processes, and structures has been broadly applied to space, defense, aerospace, civil and energy industries. Some of these applications, such as nuclear power plant structures, require ultrasound NDE operated at elevated temperatures (>700°C). However, conventional ultrasound transducers made with PZT or PMN-PT materials can only tolerate temperatures up to 200°C.

In this work, we propose a new ultrasound NDE method using photoacoustic-laser-source as an ultrasound transmitter and HT ultrasonic transducer made of aluminum nitride (AlN) single crystal as an acoustic receiver. AlN has shown its promise for HT applications because of its high Curie temperature (>2000°C) and high thermal resistivity of the dielectric and piezoelectric constants at temperatures up to 800°C. Furthermore, the laser ultrasound system with the specially designed patches (e.g. carbon-nano-particle (CNP)/PDMS composite) has been demonstrated to generate broad-band and high-amplitude ultrasound waves propagating over the entire region of the target structure. As a preliminary test at the room temperature, 10 and 30 times higher sensitivity (peak-to-peak voltage) can be received by a piezoelectric receiver when using the PDMS-only and CNP/PDMS patch, respectively, compared with no-patch condition. Further tests will be conducted by testing a long Al and stainless steel bars with AlN transducer on the surface at one end (inserted into a HT furnace), and the laser ultrasound patch on the surface at the other end (outside of furnace). Stainless steel bars with defects will be prepared and tested using this configuration for HT ultrasound NDE at temperatures up to 800°C.

10169-54, Session 12A

3D printed metamaterial design to focus wave energy in thin plates

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Acoustic metamaterials are periodic and composite structures that can block, direct and strengthen propagating elastic waves. They are made of two or more materials with different elastic properties. The periodic structure can exhibit certain band gaps that can be used to manipulate wave field. When a wave field interferes with the periodic structure, the acoustic frequencies within the band gap of the periodic structure cannot penetrate into the periodic structure, and reflect back to the original domain. This property can be utilized to control the direction of certain frequencies of elastic waves. In this research, the periodic and composite structure is made of aluminum plate and polymer cylinders manufactured using 3D printing. The ability to block and redirect elastic waves is numerically and experimentally demonstrated. Wave field focusing reduces the wave attenuation, which allows increasing the distance of acoustic sensors for damage detection in large-scale structures.

10169-55, Session 12A

Development of a nonlinear ultrasonic NDE technique for detection of kissing bonds in composites

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The development of low-cost, bonded, assembly of composite aerospace structures ideally requires an NDE method to detect the presence of poor quality, weak bonds or kissing bonds. Such interfaces can introduce nonlinearity as a result of contact nonlinearity where an ultrasonic wave is distorted when it interacts with the interface. In general, the nonlinear elastic behavior of these interfaces will result in the generation of harmonics but they can be lost among the harmonics generated by other nonlinearities present in the experimental system. The technique developed in this research is a non-collinear method; this involves the interaction of two ultrasonic beams, and it allows the removal of virtually all system nonlinearity except for that produced in the region where the two beams overlap. The frequencies of the two beams and the angle between are varied during the experiment. By measuring the nonlinear mixing response as these two parameters are swept through a 'fingerprint' of the nonlinear properties in the interaction region can be obtained. This fingerprint has been shown to contain information about the bulk material and the interface status. Work is ongoing to understand which features in the fingerprints reliably correlate with particular material or interface properties. To build this understanding a highly simplified kissing bond, a compression loaded aluminium-aluminium interface, has been tested. Modelling of the nonlinear behavior of solid aluminium has also been conducted.

10169-56, Session 12A

Tree root detection from ground surface vibration measurements

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A rapid development of urban infrastructure in past decades together with a relatively recent growth of awareness of its impact on the natural environment result in an increased interest in non-destructive ground interrogation methods. Underground space in cities is very densely populated by various types of infrastructure but it is also a home for tree roots. Tree root damage is a very well known issue in civil engineering and can emerge as road surface fracture, building foundations disintegration or pipe penetration, among others. For new developments it is essential to avoid any interference with roots not only since they may cause costly damage but also because their discovery during construction may pose additional complications related to the natural environment protection. In this paper we investigate the feasibility of using a vibroacoustic method for tree root mapping. The core of the idea is that the mechanical waves induced by an excitation mechanism acting on the tree trunk propagate to the roots and then radiate into the surrounding soil. Owing to that, the response measured at the ground surface contains the contribution of waves radiating from roots and can be used for mapping their extent. We conduct a finite element analysis of the trunk-root-soil system determining the dominant wave fields contributing to the ground surface response. Then, we report a set of experiments on a 'purpose-built' physical root model. An instrumented root buried at a known depth is excited using various techniques with both root and ground responses acquired. These preliminary results both demonstrate the technique and shed light on related challenges and limitations.

10169-57, Session 12A

Prognostics of railway prestressed concrete sleeper damage using acoustic emission technology

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Flexural damages in railway prestressed concrete sleepers are often hidden from visual inspections during track monitoring and maintenance activities. Often, small cracks can sometimes be generated due to aggressive dynamic actions. These cracks indicate a level of serviceability of the railway sleepers. Severe cracks can impair rail gauge stability due to large rail inclinations. This gauge instability can cause train derailments, especially in curves and transitions where lateral train force incurs coincide with unstable two point contacts between wheel and rail. An attempt to develop a non-destructive prognostic tool for structural health of prestressed concrete sleepers in railway tracks using the vibration responses has been established at the University of Birmingham, UK. The fundamental principle is to have better insight into the acoustic emission when sleepers crack and then become damage. This paper therefore investigates the prognostics of railway concrete sleepers based on acoustic energy of railway prestressed concrete sleeper when its cracks emerge. Experimental modal analysis has also been used to evaluate the modal parameter changes of the prestressed concrete sleeper in the frequency band between 0 and 2,000 Hz. The railway concrete sleepers have been subjected to ultimate static loading to stimulate structural failures. Acoustic emission traits and dynamic modal parameters of the sleepers have been investigated before and after the flexural damage. This insight is extremely essential in order to establish a decision-making guideline for rail track engineers and managers to monitor and maintain structural integrity of railway track and its components.

10169-58, Session 12A

Ultrasonic waves in biaxially stressed multi-layered and 1D phononic structures

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Elastic wave velocities as a function of applied stress are analysed in multilayered and 1-D phononic structures. The analysis is conducted by the means of the acoustoelasticity theory for isotropic elastic structures with application of this theory to stable formulation of stiffness and hybrid matrix methods for the eigenvalue analysis in the stressed elastic structures. The reformulated matrix methods are used for obtaining modal solutions, reflection and transmission coefficients for different multilayered media cases. Floquet wave analysis is presented for the stressed 1-D phononic structures. The analysis is supported by numerical examples.

10169-59, Session 12A

Finite element simulation of ultrasonic waves in corroded reinforced concrete for early-stage corrosion detection

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In reinforced concrete (RC) structures, corrosion of steel rebar introduces internal stress at the interface between rebar and concrete, ultimately leading to debonding and separation between rebar and concrete. Effective early-stage detection of steel rebar corrosion can significantly reduce maintenance costs and enable early-stage repair. In this paper, ultrasonic detection of early-stage steel rebar corrosion inside concrete is numerically investigated using the finite element method (FEM). Commercial FEM software (ABAQUS) was used in all simulation cases. Steel rebar was simplified and modeled by a cylindrical structure. 1MHz ultrasonic elastic waves were generated at the interface between rebar and concrete. An eight-node finite element (C3D8) was adopted in all FE models. Formation of surface rust in rebar was modeled by changing material properties and expanding element size in order to simulate the rust interface between rebar and concrete and the presence of interfacial stress. Various surface rust (corroded regions) locations and different sizes of surface rust were considered. Transient and frequency responses of surface displacement were studied. From our simulation result, it was found that corrosion product is most detectable when the rust is located between a transducer and a receiver (transmission mode). Attenuation of transmitted and reflected ultrasonic waves exhibited different patterns in the longitudinal axis and in the radial axis.

10169-60, Session 12A

Development of an ultrasonic nondestructive Inspection method for impact damage detection in composite aircraft structures

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High Energy Wide Area Blunt Impact (HEWABI) due to ground service equipment can often occur in aircraft structures causing major damages. These Wide Area Impact Damages (WAID) can affect the internal components of the structure, hence are usually not visible nor detectable by typical one-sided NDE techniques and can easily compromise the structural safety of the aircraft.

In this study, the development of an NDI method is presented together with its application to impacted aircraft frames. The HEWABI from a typical ground service scenario has been previously tested and the desired type of damages have been generated, so that the aircraft panels could become representative study cases. The need of the aircraft industry for a rapid, ramp-friendly system to detect such WAID is here approached with guided ultrasonic waves (GUW) and a scanning tool that accesses the whole structure from the exterior side only.

The wide coverage of the specimen provided by GUW has been coupled to a differential detection approach and is aided by an outlier statistical analysis to be able to inspect and detect faults in the challenging composite material and complex structure. The results will be presented and discussed with respect to the detection capability of the system and its response to the different damage types. Receiving Operating Characteristics curves (ROC) are also produced to quantify and assess the performance of the proposed method.

Ongoing work is currently aimed at the penetration of the inner components of the structure, such as shear ties and C-frames, exploiting different frequency ranges and signal processing techniques. From the hardware and tool development side, different transducers and coupling methods, such as air-coupled transducers, are under investigation together with the design of a more suitable scanning technique.

10169-61, Session 12A

Nondestructive evaluation of defects in carbon fiber reinforced polymer (CFRP) composites

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Carbon fiber reinforced polymer (CFRP) composites are increasingly used in aerospace applications due to its superior mechanical properties and reduced weight. Adhesive bonding is commonly used to join the composite parts since it is capable of joining incompatible or dissimilar components. However, insufficient adhesive or contamination in the adhesive bonds might occur and pose as threats to the integrity of the plane during service. It is thus important to look for suitable nondestructive testing (NDT) techniques to detect and characterize the sub-surface defects within the CFRP composites. Some of the common NDT techniques include terahertz (THz), ultrasonic techniques and thermography. In this work, we report the use of the abovementioned techniques (i.e. THz, ultrasonic techniques and thermography) for improved interpretation of the results.

10169-62, Session 12A

Nondestructive evaluation of pipes with dent using ultrasonic guided waves

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Local geometrical imperfections such as dent have been shown to be critical for pipelines used in the oil and gas industries. Dents are known to affect the integrity of the pipes by deteriorating its buckling strength which in turn affects their load carrying capacity. Typical inspection techniques such as ultrasound, magnetic flux leakage etc. are periodically used to qualify the integrity of the pipeline with focus on detecting cracks or crack like features. Currently, dents as defect features remain largely uncharacterized due to their signatures either being ignored or being wrongly classified as cracks. The interaction of guided waves with cracks have been widely studied and well understood but defects like dent need further study.

Here we investigate the interaction of circumferentially travelling shear horizontal guided waves (CSH0) with dents of varying sizes. For the first time dents have been modelled using 3D finite element simulations and the visualization shows waves travel along the dent profile with possible mode conversion and has been validated by experiments. In addition, we have also studied the sensitivity of the CSH0 mode for different dent depth and width. We also made an attempt to predict the buckling strength of a cylindrical shell using ultrasonic guided wave parameters

10169-63, Session 12B

Reliably detectable flaw size for NDE methods that use calibration

Ajay M. Koshti, NASA Johnson Space Ctr. (United States)

Probability of detection (POD) analysis is used in assessing reliably detectable flaw size in nondestructive evaluation (NDE). MIL-HDBK-1823 and associated mh1823 POD software gives most common methods of POD analysis. In this paper, POD analysis is applied to an NDE method, such as eddy current testing, where calibration is used. NDE calibration standards have known size artificial flaws such as electro-discharge machined (EDM) notches and flat bottom hole (FBH) reflectors which are used to set instrument sensitivity for detection of real flaws. Real flaws such as cracks and crack-like flaws are required to be detected using these NDE methods. A reliably detectable crack size is required for safe life analysis of fracture critical parts. Therefore, it is important to correlate signal responses from real flaws with signal responses form artificial flaws used in calibration process to determine reliably detectable flaw size. The paper provides a procedure and example of using MIL-HDBK-1823 methods to determine reliably detectable crack size when calibration on artificial flaws is used to set the technique sensitivity.

10169-64, Session 12B

Foundation stiffness in the linear modeling of wind turbines

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Effects of foundation stiffness on the linear vibrations of wind turbine systems are of concerns for both planning and construction of wind turbine systems. Current study performed numerical modeling for such a problem using linear spectral finite elements. The effects of foundation stiffness were investigated for various combinations of shear wave velocity of earth, size of tower base plate, pile length and pile diameter. Multiple piles are also included in the models such that the foundation stiffness can be analyzed more realistically. The results indicate that the shear wave velocity of earth and the size of tower base plate have notable effects while pile length has limited effect on the dominant frequency of the turbine-tower system. Simulation based on multiple layers of earth and rock will also be presented. Preliminary results show that the stiffness of the turbine-tower system is affected significantly by the shear velocity of the top layer earth.

10169-65, Session 12B

Research on public participant urban infrastructure safety protection system using smartphone

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Currently more and more people concerned about the safety of major public security. The urban infrastructure safety is related to every People's Daily lives. Public participant urban infrastructure safety monitoring and investigation has become a trend in the era of big data. In this paper, public participant urban infrastructure safety protection system based on smart phones is proposed. The system makes it possible to public participant disaster data collection, monitoring and emergency evaluation in the field of disaster prevention and mitigation. And the multi-parameter monitoring and detection system is based on smartphone sensors. The smartphone built-in multi-parameter sensors mainly include images, text, video, angle, acceleration, etc. The system has four main functions. Firstly, the system is used to monitor the structural acceleration, angle and other vibration information. Secondly, it can extract structural deformation, cracks and other damage information. Thirdly, it can implement disaster emergency communications based on smartphone Bluetooth wireless technology without network. The last, it can make the city safety early warning. Wherever you are, you who logged in the mobile client can monitor the urban infrastructure to obtain disaster information. After monitoring, the collection data is uploaded to the website to create urban safety information database. Then professionals analyze the monitoring data and make the city safety warning. So we can realize urban infrastructure phone perceived risk damage feature extraction and monitoring. And we can also achieve big data collection, sharing and analysis. Finally the system supports big data analysis processing, structure safety assessment and city safety early warning.

10169-66, Session 12B

Optimizing probability of detection point estimate demonstration

Ajay M. Koshti, NASA Johnson Space Ctr. (United States)

The paper provides discussion on optimizing probability of detection (POD) demonstration experiments using point estimate method. The optimization is performed to provide acceptable value for probability of passing demonstration (PPD) and achieving acceptable value for probability of false (POF) calls while keeping the flaw sizes in the set as small as possible. POD Point estimate method is used by NASA for qualifying special NDE procedures. The point estimate method uses binomial distribution for probability density. Normally a set of 29 flaws of same size within some tolerance are used. Traditionally largest flaw size in the set is considered to be a conservative estimate of the flaw size with minimum 90% probability and 95% confidence. The flaw size is denoted as a90/95PE. The paper investigates relationship between range of flaw sizes in relation to a90, i.e. 90% probability flaw size, to provide a desired PPD. The range of flaw sizes is expressed as a proportion of the standard deviation of the probability density distribution. In general, it is concluded that if probability of detection increases with flaw size, average of 29 flaw sizes would always be larger than or equal to a90 and is an acceptable measure of a90/95PE.

If NDE technique has sufficient sensitivity and signal to noise ratio then the 29 flaw-set can be optimized to meet requirements of minimum required PPD, maximum allowable POF, requirements on flaw size tolerance about mean flaw size and flaw size detectability requirements. The paper provides procedure for optimizing the point estimate flaw-set.

10169-67, Session 12B

Crack detection flaw size parameter modeling for x-rays at grazing angle to crack faces

Ajay M. Koshti, NASA Johnson Space Ctr. (United States)

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. An alternate approach is to use a more complex flaw size parameter. Earlier x-ray flaw size parameter models by the author did not include scattering effects in detection of cracks. The x-ray flaw size parameter model, given here, investigates one of scattering effects namely specular reflectivity of x-rays impinging on crack faces at grazing angle. Reflectivity of x-rays at low grazing angle to crack faces is almost 100%. If crack faces are smooth and flat, the grazing angle x-rays channel between the crack faces. The paper models the specular reflection to study its effect on contrast of x-ray image of the crack. The channeling of x-rays can improve x-ray image contrast significantly. Normalized exposure and image width are used to calculate the flaw size parameter. Reflectivity of grazing angle x-rays can be used to improve x-ray crack detectability in thin low density materials such silicon and gallium arsenide.

10169-69, Session 12B

Smart structures: modeling, analysis, and control with different strategies

Nader Ghareeb, Mohamed Gaith, Sayed Mohamad Soleimani, Australian College of Kuwait (Kuwait)

Reducing vibration in flexible structures has become a pivotal engineering problem and shifted the focus of many research endeavors. One technique to achieve this target is to implement an active control system. A simple active control system comprises a vibrating structure, a sensor to perceive the vibration, an actuator to counteract the influence of disturbances causing vibration, and finally a controller to generate the appropriate control signals. In this work, different linear controllers are used to attenuate the vibrations of a cantilevered smart beam excited by its first eigen frequency. The smart structure proposed in this paper is composed of a cantilevered steel beam, an adhesive or bonding layer, and a piezoelectric actuator. The static deflection of the structure is derived as function of the piezoelectric voltage, and the outcome is compared to theoretical and experimental results from literature. A finite element (FE) model of the smart beam is initially created and then modified by using experimental data. The FE model is then reduced to a super element (SE) model with a finite number of degrees of freedom (DOF). Controllers are applied directly to the SE, as well as to the extracted state-space (SS) model for validation. Finally, results are presented and compared.

10169-70, Session 12C

Excitation and reception of non-dispersive guided waves using face-shear d24 mode piezoelectric transducers

Hongchen Miao, Peking Univ. (China)

The non-dispersive fundamental shear horizontal (SH0) and torsional (T(0,1)) waves are extremely useful in guided-wave-based inspection technique. However, excitation or generation of SH0 and T(0,1) waves using piezoelectrics is always a challenge. In this work, firstly, a newly defined face-shear d24 PZT wafer is proposed to excite and receive SH0 wave mode. The d24 wafer is in-plane poled and its working electric field is applied along another orthogonal in-plane direction. Both finite element simulations and experiments show that single SH0 mode can be excited by the d24 wafer symmetrically along two orthogonal directions (0° and 90°). Then an omnidirectional SH0 wave piezoelectric transducer (OSH-PT) is furtherly developed which consists of a ring array of twelve face-shear d24 trapezoidal PZT elements. Results show that the proposed OSH-PT exhibits good omnidirectional properties, no matter it is used as a SH0 transmitter or a SH0 wave receiver. Finally, the development of a T(0,1) wave piezoelectric transducer based on the d24 elements for pipes is described. Both finite element simulations and experiments on pipes show that a ring of piezoelectric face-shear d24 elements can be used to excite single T(0,1) mode and suppress all the unwanted non-axisymmetric modes. This work may greatly promote the applications of SH0 and T(0,1) waves in nondestructive testing (NDT) and structural health monitoring (SHM).

10169-71, Session 12C

Laser-based piezoelectric structural health monitoring system for remote I-beam crack detection

Chen Zhang, Haifeng Zhang, Univ. of North Texas (United States)

As one of the most important engineering structural materials, I-beam has been widely used in various areas. Therefore, a valid sensing system for I-beam crack detection is urgently required for safety and function reasons. This paper proposes an innovative sensing system, which is based on the piezoelectric effect and laser sensing system. Different from other energy diffusivity approaches, the proposed sensing system is employing a piezoelectric disk as an actuator and a laser vibrometer for sensing. Lab tests are carried out and the vibrational properties are studied to characterize the health status of the I-beam. By investigating the amplitude change and/or phase shift of the detected signals, the crack size and position can be characterized and analyzed. The new detection method has been validated by conventional piezoelectric sensing method. Since laser beam can be generated and detected remotely, this technology would allow the remote monitoring of rail cracks. Moreover, rather than attaching a piezoelectric sensor on a fixed position, laser beam could be monitored in multiple positions and therefore enable flexible and fast monitoring. The proposed sensing system can also be applied to buildings, bridges, nuclear power plant structures and subway systems.

10169-72, Session 12C

Sensing capabilities of piezoelectric wafer active sensors in extreme nuclear environment

Mohammad Faisal Haider, Bin Lin, Lingyu Yu, Victor Giurgiutiu, Univ. of South Carolina (United States)

There is considerable demand for structural health monitoring (SHM) at locations where there are substantial radiation fields such as nuclear reactor components, dry cask storage canister, irradiated fuel assemblies, etc. Piezoelectric wafer active sensors (PWAS) have been emerged as one of the major SHM sensing technologies. In order to use PWAS to perform SHM in nuclear environment, radiation influence on sensor and sensing capability needs to be investigated to assure the reliability of the PWAS based method. Radiation may cause degradation or even complete failure of sensors. Gamma radiation is one of the major radiation sources near the nuclear environment. Therefore, experimental investigation was completed on the radiation endurance of piezoelectric sensors. The irradiation test

was done in a Co-60 Gamma Irradiator (by JL Shepherd and Associate). Lead Zirconate Titanate (PZT) and Gallium Orthophosphate (GaPO4) PWAS were exposed under gamma radiation at 100 Gy/hr rate for 20 hours. Electro-mechanical (E/M) impedance/admittance signatures and electrical capacitance were measured to evaluate the PWAS performance before and after every 4 hours exposure to gamma radiation. PWAS were kept at room temperature for 6 days after each 4 hours radiation exposure to investigate the effect of time on PWAS after exposure. It is found that, for PZT-PWAS, slight variation in resonance and anti-resonance frequency for both in plane and thickness mode was observed. Where, the changes in anti- resonance and resonance amplitudes are larger and for GaPO4, E/M impedance/ admittance spectra don't show any reasonable change after gamma irradiation. The piezoelectric material degradation was also investigated by microstructural and crystallographic study. Scanning Electron Microscopy (SEM) system was used to visualize the cross section of PWAS and X-ray powder diffraction (XRD) spectrum was used to identify change in crystal structure, unit cell dimension and symmetry.

10169-73, Session 12C

Damage size and depth estimation using laser scanning and wavenumber based signal processing

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This study presents the process of damage size and depth estimation using laser scanning with a single frequency excitation and wavenumber analysis on plate like structures. Using a single, fixed frequency (>50 kHz) excitation from a mounted piezoelectric transducer, the full standing wave-field could be obtained using a Laser Doppler Vibrometer (LDV) with a mirror tilting device. After scanning in high-speed, a wavenumber filtering is performed to determine certain wavenumber components, which could be used for damage detection. The two wavenumber based signal processing are then carried out for damage size estimation: the local wavenumber mapping and acoustic wavenumber spectroscopy. In order to estimate the depth of the damaged area, a Lamb wave equation is employed and the wavenumber components are converted into the depth information. Several experiments are performed on thin aluminum plates and steel pipes to demonstrate the concept. The results demonstrate that the technique is very effective in quantitative damage estimation with a high interrogation speed.

10169-74, Session 13A

The evaluation of ordinary Portland cement concrete subject to elevated temperatures in conjunction with acoustic emission and splitting tensile test

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The research objective was to evaluate Ordinary Portland Cement concrete subject to various elevated temperatures. Single OPC concrete mixture with water to cementitious (w/c) equal to 0.51 was proportioned. Concrete specimens were cast and placed in the curing tank in which water was saturated with calcium hydroxide. After ninety days of moist-cure, three elevated temperatures, namely 300, 600, and 900-°C, were carried out upon hardened concrete specimens. Furthermore, two post-damaged conditions were executed to recover damaged concrete specimens: one was to re-cure under 23°C with 50% humidity in a controlled environmental chamber and the other was to re-cure in the same curing tank. Acoustic emission apparatus coupled with the splitting tensile test was found able to assess damaged concrete. Before concrete subject to elevated temperatures, the development of indirect tensile strength versus displacement diagram fit well with the tendency of AE energy release. It was found there was a large amount of AE energy released when stress and displacement diagram developed about 40-50%. As such could be identified as the onset of fracture and the plain concrete generally exhibited a quasi-brittle fracture; however when concrete specimens were subject to elevated temperatures, neither the damaged nor recovered concrete specimens displayed the similar fracture pattern of plain concrete.

10169-75, Session 13A

Ultrasonic velocity testing of steel pipeline welded joints

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In general the ultrasonic techniques have been used to determine the mechanical properties of materials on based of their relationship with metallurgical characteristics. In this research work, the relationship between ultrasonic velocity and phased array and the microstructure of steel pipeline welded joints is investigated. Measurements of ultrasonic wave velocity were made as a function of the location across the weld. Hardness measurements were performated in an attempt to correlated with ultrasonic response. In addition, the coarse and dendritic grain structure of the weld material is extreme and unpredictably anisotropic. Thus, due to the acoustic anisotropy of the crystal itself weld material of studied joints is anisotropic, too. Such structure is no longer direction-independent to the ultrasonic wave propagation; therefore, the ultrasonic beam deflects and redirects and the wave front becomes distorted. Thus, the use of conventional ultrasonic testing techniques using fixed beam angles is very limited and the application of conventional ultrasonic phased array techniques becomes desirable.

10169-76, Session 13A

Pressure-tension test for assessing fatigue in concrete

Sayed Mohamad Soleimani, Australian College of Kuwait (Kuwait); Andrew J. Boyd, Andrew Komar, McGill Univ. (Canada)

In a pressure-tension test, a cylindrical concrete specimen is inserted into a cylindrical steel jacket, with a rubber "O" ring seal at each end to prevent gas leakage. Gas pressure is then applied to the curved surface of the concrete cylinder, leaving the ends free. As the gas pressure is increased, the specimen eventually fractures across a single plane transverse to the axis of the cylinder. The gas pressure at fracture may then be considered as the tensile strength of the concrete.

In this study, the pressure-tension test is used to study fatigue in concrete. A total of 22 standard concrete cylinders (100 mm x 200 mm) were tested. Both dry and wet specimens have been studied. Low-cycle loading, which involves the application of a few load cycles at high stress levels – such as a concrete structure under earthquake load, has been used in this study. It was found that the concrete specimens in a low-cycle loading fail after only a few cycles of loading and interestingly at a stress level lower than the maximum value applied in the cyclic loading. In addition, non-destructive testing (NDT) was performed to determine the progressive damage due to tensile load in concrete cylinders using Ultrasonic Pulse Velocity (UPV). It was found that UPV can be used to evaluate the damage in concrete even after the application of a very low-level of tensile stress – as low as 10% of its tensile strength.

10169-77, Session 13A

2D numerical model for analysis of possible second-order interactions of ultrasonic waves with a presence of fluid and solid interface

Andriejus Demcenko, Univ. of Glasgow (United Kingdom); Michael Mazilu, Univ. of St. Andrews (United Kingdom); Rab Wilson, Jonathan M. Cooper, Univ. of Glasgow (United Kingdom)

Non-collinear ultrasonic wave mixing for nonlinear ultrasonics is used for various NDT&E applications to characterize structure/material state. Experiments are frequently conducted using immersion ultrasonic techniques. In this configuration various wave modes are generated at the fluid-solid interface. We have characterised this scenario experimentally and developed a 2D numerical model to analyse the influence of the interface on the possible second-order interactions of the ultrasonic waves. The model is based on the decomposition of the ultrasonic wave into a superposition of monochromatic plane waves. As these waves propagate through the interface and solid, their nonlinear interaction defines a flow of energy between the different modes. Using the Murnaghan's nonlinear interaction potential, we have studied the efficiency of this energy transfer as a function different geometrical parameters.

10169-78, Session 13A

Electrical resonance eddy current sensor for submillimeter defect detection

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Electrical resonance based EC methods are being investigated and developed for the detection of sub-millimeter surface defects in low conductivity material such as superalloy in aircraft. The probe has high sensitivity due to the noise elimination by evaluate the relative resonance shift on the impedance change cause by material properties variance. This method has reported analytically with experimental validation recently. In this paper, we investigated on the sensitivity of impedance change due to the variation of sensor parameters such as ferrite core and coil gap dimension as well as liftoff of the detection system using full wave 3D electromagnetic finite element simulation with integrated circuit model simulator. The finite element simulation is to study the probe behavior while the circuit model simulator is used to investigate the influence of the external component such as capacitance and resistance in the detection system. This study contributes to the optimization and sensitivity enhancement of the detecting system. Thus the defect beyond 0.8 mm, which is the critical defect of the most of the low conductivity material detect using conventional eddy-current method, can be detected. Carefully detection is needed in order to minimise the failure and ensure its economic viability and increasing the service life of the device.

10169-79, Session 13B

Measurement of mechanical properties of metallic glass at elevated temperature using sonic resonance method

Suresh Kaluvan, Haifeng Zhang, Sanghita Mridha, Sundeep Mukherjee, Univ. of North Texas (United States)

Metallic glass is a metal with amorphous crystalline structure as similar to the glass materials. The metallic glasses produced with a unique chemical composition are currently emerging as a new class of metallic materials for hefty structural and functional use. The mechanical properties of bulk metallic glasses, including their superior yield strength and hardness, excellent corrosion, wear resistance, and inability to plastic deformation have been a subject of fascination for scientists and engineers. The Young's modulus and Shear modulus at elevated temperatures are important to study the application aspects of this material, however, the study of mechanical properties at elevated temperature are not much is reported in the literature. We have adopted a nondestructive sonic resonance measurement method to Young's modulus and Shear modulus of bulk solid metallic glass at elevated temperatures. The measurement system is designed using a laser displacement sensor to detect the sonic vibration (displacement and frequency) produced by external loudspeaker on the specimen placed inside the high-temperature furnace. The OMICRON Bode-100 Vector Network Analyzer is used to sweep the frequency and its output is connected to the loudspeaker which vibrates the material at its flexural mode and thickness shear mode of vibration. The LABVIEW interfaced Polytec OFV-505 laser displacement sensor is used to capture the frequency response of the material at various temperatures. The flexural and shear mode frequency shift due to the temperature variation is used to derive the Young's modulus and Shear modulus of a bulk solid material. The performance of the proposed technique is experimentally evaluated for the temperature range from 50°C to 350°C. The metallic glass with composition of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ has the Young's modulus reduction from 100GPa to 94GPa for the 300°C temperature span. Similarly, the Shear modulus decreases from 38.5GPa to 36GPa for the 300°C temperature increment.

10169-80, Session 13B

The effect of pre-stresses on guided wave propagation in plates

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Pre-stresses are frequently introduced into structures for a variety of reasons. Acoustoelastic techniques have been proposed to characterize the state of pre-stress in such structures. In plate-like structures the effect of stresses on the speed of propagation of guided waves can be exploited to characterize the state of pre-stress. In this study, the effect of pre-stresses with gradients on the propagation speed of guided waves is examined. In the context of acoustoelasticity, an isotropic plate with a pre-stress gradient behaves like a laminated anisotropic material. The acoustoelastic constants are a function of direction of wave propagation and are also dependent on the thickness coordinate. Acoustoelastic theory and laminated anisotropic plate theory are combined in this study. The inhomogeneity of constitutive behavior through the thickness of the plate is modeled suitably using a transfer matrix method. The effect of pre-stress gradient magnitudes on dispersion curves of symmetric and antisymmetric modes of guided wave propagation is demonstrated. Dispersion curves are presented for an aluminum plate as a function of magnitude and direction of applied pre-stress gradients.

10169-81, Session 13B

Embedded FBG sensor configuration for space environment hazard exposure monitoring of CFRP composites

Yurim Park, Hyunseok Kwon, Pratik Shrestha, Chun-Gon Kim, KAIST (Korea, Republic of)

Composite materials have unique advantages especially for space environment applications. However, they exhibit failure modes and various cracks/delaminations which are predominantly difficult to detect visually, thus, an effective means to assess the integrity of such composite materials exposed to space environment hazards as well as hypervelocity impact

by debris and micrometeoroids are necessary for the long term reliability of composites for space applications. FBG sensors are immune to various environments and are advantageous for space applications. This study investigates FBG sensor configurations embedded in CFRP to monitor the exposure of the material to such hazardous space environments and impact events.

10169-82, Session 13B

Approximating the coefficient of thermal expansion of concrete using time periods of uniform thermal gradient

Jack Reilly, Hiba Abdel-Jaber, Princeton Univ. (United States); Matthew Yarnold, Tennessee Technological Univ. (United States); Branko Glisic, Princeton Univ. (United States)

Structural Health Monitoring aims to assess the integrity of a structure from a combination of sensor data and analytic techniques. Many methods are concerned with quantifying the elastic response of the structure, treating temperature changes as noise in the analysis. While these elastic profiles do demonstrate a portion of structural behavior, the thermal loads on a structure can induce comparable strains to elastic loads. Understanding this relationship between the temperature of the structure and the resultant strain and displacement can provide in depth knowledge of the structural condition. Necessary for this form of analysis is the Coefficient of Thermal Expansion (CTE). Many times with concrete, the actual amount of expansion with temperature in-situ varies from the given values for the CTE. To accurately characterize the relationship between temperature and strain on a structure, the actual thermal behavior of the structure needs to be analyzed to determine the rate of thermal expansion in the material. This rate can vary for different parts of a structure. In a case of linear free expansion, the strain in the structure should be linearly related to the temperature change. Thermal gradients in a structure can affect this relationship, as they induce curvature and deplanations in the cross section. The aim of this paper is to create a method for filtering out the time periods with thermal gradients, and thus enable an accurate determination of the CTE.

10169-83, Session 14

Vision-based damage identification of impact damage in a composite sandwich structure

Huan-Yu Chang, Fuh-Gwo Yuan, National Institute of Aerospace (United States)

A vision-based damage detection technique was proposed for the identification of damages in composite honeycomb structures. The motion above the damage area extracted from the wave field image with the developed image decomposition and image signal processing method reveals rich information to determine damage severity.

The standing wave prevailed at its resonant frequencies above the barely visible impact damage (BVID) on the surface of a CFRP/honeycomb composite sandwich plate, which was excited by a Q-Switch Nd:YAG pulse laser system for generating a broad-band guided wave, and the wavefield was captured by a Laser Doppler Vibrometer (LDV). With the developed image processing technique, the wavefield image that contains incident waves, reflected waves and standing waves could be separated from different wavenumber vectors and propagating directions. Phases, orientations and resonant frequencies derived from the separated standing wave were taken advantage of, for either emphasizing or magnifying the motion and illustrating the modal behavior on the damage surface. The barely visible impact damage (BVID) of the composite structure was therefore "visible" with the developed technique.

10169-84, Session 14

A feasibility study of damage detection in beams using high-speed camera

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In this paper a method for damage detection in beam structures using high-speed camera is presented. Traditional methods of damage detection in structures typically involve contact (i.e., piezoelectric sensor or accelerometer) or non-contact sensors (i.e., laser vibrometer) which can be costly and time consuming to inspect an entire structure. With the popularity of the digital camera and the development of computer vision technology, video cameras offer a viable capability of measurement including higher spatial resolution, remote sensing and low-cost. In the study, a damage detection method based on the high-speed camera was proposed. The system setup comprises a high-speed camera and a line-laser which can capture the out-of-plane displacement of a cantilever beam. The cantilever beam with an artificial crack was excited and the vibration process was recorded by the camera. A methodology called motion magnification, which can amplify subtle motions in a video is used for modal identification of the beam. A finite element model was used for validation of the proposed method. Suggestions for applications of this methodology and challenges in future work will be discussed.

10169-85, Session 14

A novel optical investigation technique for railroad track inspection and assessment

Alessandro Sabato, Christopher H. Beale, Christopher Niezrecki, Univ. of Massachusetts Lowell (United States)

Track failures due to cross tie degradation or loss in ballast support may result in a number of problems ranging from simple service interruptions to derailments. Structural Health Monitoring (SHM) of railway track is important for safety reasons and to reduce downtime and maintenance costs. For this reason, novel and cost-effective track inspection technologies for assessing tracks' health are currently insufficient and needed. Advancements achieved in recent years in cameras technology, optical sensors, and image-processing algorithms have made machine vision, Structure from Motion (SfM), and three-dimensional (3D) Digital Image Correlation (DIC) systems extremely appealing techniques for extracting structural deformations and geometry profiles. Therefore, optically based, non-contact measurement techniques may be used for assessing surface defects, rail and tie deflection profiles, and ballast condition. In this study, the design of two camera-based measurement systems is proposed for crossties-ballast condition assessment and track examination purposes. The first one consists of four pairs of cameras installed on the underside of a rail car to detect the induced deformation and displacement on the whole length of the track's cross tie using 3D DIC measurement techniques. The second consists of another set of cameras using SfM techniques for obtaining a 3D rendering of the infrastructure from a series of two-dimensional (2D) images to evaluate the state of the track qualitatively. The feasibility of the proposed optical systems is evaluated through extensive laboratory tests, demonstrating their ability to measure parameters of interest (e.g. crosstie's full-field displacement, vertical deflection, shape, etc.) for assessment and SHM of railroad track.

10169-86, Session 14

Defect visualization in CFRP-bonded concrete by using high speed camera and motion magnification technique

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High speed camera has the unique capacity of recording fast-moving objects. By using the video processing technique (e.g. motion magnification), the small motions recorded by the high speed camera can be visualized. The combined use of video camera and motion magnification technique is strongly suggested for structural inspection, due to the capability of remote detection, the operational convenience and the cost-efficiency. This paper presents a nondestructive testing (NDT) method which is based on the surface motion analysis of high speed video and can evaluate the defect in CFRP-bonded concrete system. In this study, six near-surface defects (various sizes) have been made in the specimen. Acoustic wave excitation through white noise is required to initiate the vibration of CFRP-bonded concrete system at the defect regions. The entire structural surface under acoustic excitation is recorded by a high-speed camera and the surface motion recorded through video is amplified by motion magnification technique. The defect location and the defect size can be visualized in the post-processed video. It is demonstrated that the tiny motion in all defect regions can be observed clearly in the post-processed video with motion magnification technique. This validates the effectiveness of using high speed camera for defect detection in CFRP-bonded concrete system.

10169-87, Session 15

Damage severity assessment of wind turbine blades through fuzzy finite element model updating

Heather Turnbull, Piotr Omenzetter, Univ. of Aberdeen (United Kingdom)

The recent shift towards development of clean, sustainable energy sources has provided a new challenge in terms of structural safety and reliability: with aging, manufacturing defects, harsh environmental and operational conditions, and extreme events such as lightning strikes wind turbines can become damaged resulting in production losses and environmental degradation. Consequences of damage can be catastrophic therefore rigorous testing and maintenance regimes are required.

Current practice for Non-Destructive Evaluation (NDE) of wind turbines include visual examinations, acoustic emission and ultrasonic testing. Many available testing methods are known to be subjective, difficult to implement in remote areas and can fail to detect damage occurring between predefined maintenance intervals.

Due to the limitations of the currently available aforementioned NDE methods, the ability to monitor remotely a wind turbines current structural state would provide great benefit. In addition to providing a more realistic representation of the structure, Structural Health Monitoring (SHM) would provide increased confidence in structural safety, enable maintenance to be scheduled as required, and increase production efficiency. Physics based SHM like calibration of Finite Element Models (FEMs) by inverse techniques is adopted in this research.

A novel contribution of this research is the application of Fuzzy Finite Element Model Updating (FFEMU) to damage severity assessment of wind turbine blades. The main advantage is the ability of FFEMU to account for uncertainty within the problem of model updating. Uncertainty quantification techniques, such as fuzzy sets, enable a more realistic and convenient mathematical representation of the various uncertainties. In contrast to finite element model updating, the fuzzy sub-level technique commonly used in FFEMU involves minimisation of an objective function at each sub-level. The objective function created includes the discrepancy between analytical and experimental modal parameters and facilitates model parameters to be conceptualised as fuzzy numbers, accounting for uncertainty. Particle swarm optimisation is used for minimising the objective function in updating.

A small-scale wind turbine blade model was updated using modal analysis results acquired through experimental testing. During this investigation, multiple damage severity extents were investigated through addition of small masses of varying magnitude to the structure. A structural change, similar to damage, was induced through addition of masses to the experimental structure and lumped mass elements to the FEM. Damage severity was assessed through FFEMU techniques using added mass parameters as the updating parameters.

10169-88, Session 15

Investigation of the stochastic subspace identification method for on-line wind turbine tower monitoring

Kaoshan Dai, Ying Wang, Jianze Wang, Tongji Univ. (China); Zhenhua Huang, Univ. of North Texas (United States); Xiaosong Ren, Tongji Univ. (China)

The strong drive to harness wind energy has recently resulted in a rapid growth of wind farm construction. Along with the growth, the increased size and flexibility of wind turbine towers induced large vibration problems. One critical consideration to control this large vibration is to avoid the resonance between the natural frequencies of the turbine tower and the passing frequencies of the rotor blade. The unique damping feature of wind turbines, which is a combination of the structural damping and the aeroelastic damping, is another key to control the large vibration of wind turbines under seismic or wind loads.

Structural health monitoring (SHM) of wind turbines has been applied in the wind energy industry to obtain their real-time vibration parameters and to ensure their optimum performance. For SHM, the accuracy of its results and the efficiency of its measurement and analysis methodology are the two major concerns. Selection of proper measurement parameters could improve such accuracy and efficiency.

The Stochastic Subspace Identification (SSI) is a widely used data processing method for SHM. This research discussed the accuracy and efficiency of SHM using SSI method to identify vibration parameters of on-line wind turbine towers. Based on a series of field test data, the influencing factors for the accuracy and efficiency were investigated, which include sampling frequencies, measurement durations, structural natural frequencies, and structural damping ratios. Proper measurement parameters, such as optimum measurement durations, are recommended.

10169-89, Session 15

Motion-blur-compensated structural health monitoring system for tunnels at a speed of 100 km/h

Tomohiko Hayakawa, Masatoshi Ishikawa, The Univ. of Tokyo (Japan)

Although high quality image of tunnel surface using vehicles is necessary for precise visual judge of abnormal parts instead of human visual inspection, efficiency and precision are in the trade off relationship. Since the amount of motion blur increases as the taken image becomes higher resolution and the driving speed of vehicle becomes faster, then it will be more difficult to take sharp images which include detailed textures. Conventional systems use considerable bright illuminations with limited exposure time, however strong illumination is dangerous for human eyes, and has possibility to prompt accident by looking away of another driver. Hence, we propose the motion blur compensated monitoring system from a vehicle by back and forth motion of galvanometer mirror to offset the vehicle speed to prolong exposure time. However, because of the lack of responsiveness of a galvanometer mirror, the system did not correspond with the maximum speed of Japanese standard tunnel in highway: the height is 7m; the speed limit 100km/h. Accordingly, we propose the method realizing precise path tracking in PID control by amplification of signal. As an experimental result of the system which is mounted on the vehicle, we confirmed significant improvement of image quality to prolong exposure time for a few millimeter order black-and-white stripes and cracks with motion blur compensation in Japanese maximum speed and standard tunnel on highway. Additionally, this result is compatible with conventional systems.

10169-90, Session 15

Hyperspectral imaging of building emissions

Masoud Ghandehari, New York Univ. (United States)

Cities determine a great deal of global energy consumption and the corresponding impact on the local and global environment. However, data with extent of coverage and level of detail required to characterize this impact is not available to inform either regulatory or compliance policies, or for planning and modeling purposes. Even in data-rich cities, there is inadequate information on the emissions of gaseous pollutant plumes. Closing those gaps with high spectral, spatial, and temporal resolution and with broad and persistent coverage is revolutionizing our understanding of the urban environment and urban energy use. This will have potentially significant impact on the health and well-being of inhabitants in densely constructed environments, and aid in tracking compliance. We carried out an eight-day campaign imaging New York City from Freedom Tower to Central Park at nearly every 3 minutes in spectral bands from 7.4 to 13.2 microns. Results revealed the emission of over 10 types of gaseous plumes. Methodology for data analysis including compensation for the atmospheric effects and estimation of concentrations is presented.

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10170-1, Session 1

Portable laser-ultrasound scanner for ultrafast, non-contact, ply-by-ply imaging of inconsistencies in aircraft composites *(Keynote Presentation)*

Lukasz Ambroziński, AGH Univ. of Science and Technology (Poland) and Univ. of Washington (United States); Ivan M. Pelivanov, Matthew O'Donnell, Univ. of Washington (United States)

Among NDT methods, only ultrasound (US) and X-ray tomography can precisely locate three-dimensional defects regardless of composite type. X-ray systems, however, are time consuming, expensive, cumbersome and require sample extraction from a component, which makes them unsuitable for field applications. Conventional US pulse-echo techniques usually require couplants or full sample immersion, which can affect overall scan speed and limit the applications where they can be used.

Laser-ultrasound (LU) has many advantages over conventional US. First, laser-generated US transients are ultra-wideband, providing much better in-depth resolution compared to conventional US transducers operated at the same characteristic frequency. Second, LU is fundamentally non-contact and removes all issues related to US coupling. Its typical disadvantages are low sensitivity, instability, low pulse repetition frequency and high cost. We have recently overcome these limitations with a new kHz rate fiber-optic LU scanner. The key component is a new fiber-optic Sagnac interferometer delivering a dramatic change in the sensitivity of US signal detection.

Inconsistences of polymer composite structure and damage induced by different impacts (collisions, hits, lightning strikes, etc.) must be evaluated to predict a component's post-impact strength and residual life-time, especially when impacts occur in structures related with human safety (in aircrafts, for example). Here we show that the scanner can provide nearly X-ray quality 3D images and locate almost all imperfections in aircraft composites at different spatial scales: image defects and impact damage with sub-ply spatial resolution, visualize pores and wrinkles and evaluate heat damage.

10170-2, Session 1

Infrared thermography to impact damaging of composite materials

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Composite materials are becoming even more popular due to their many advantages over metals. As a main advantage it is possible to create a material of given characteristics by changing either the type of matrix, or reinforcement; in this way a multitude of materials can be created. Of course, they require characterization for an appropriate exploitation. In this context, infrared thermography (IRT) represents a viable means since it is non-contact, non-intrusive and can be used to monitor the entire existence of a product, from its manufacturing process to completion as well as in-service life. In this work, IRT is used to investigate different types of composite materials which are based on either a thermoset, or thermoplastic matrix, which may be neat, or modified by addition of a relatively low amount of a specific compatibilizing agent, and reinforced with carbon, glass or jute fibres. IRT is used with a twofold function. First for non-destructive evaluation of materials before and after impact to assure absence of manufacturing defects and damage caused by the impact. In particular, non-destructive evaluation is carried out with lockin thermography which allows assessing the material conditions at different layers in a fast way. Second IRT is used to visualize thermal effects, which develop when the material is under impact. The obtained results show that it is possible to follow the material bending, delamination and eventual failure under impact.

10170-3, Session 1

Assessment of delamination in composite beam using infrared thermography, optical sensors, and terahertz technique

Katarzyna M. Majewska, Rohan N. Soman, Magdalena M. Mieloszyk, The Szewalski Institute of Fluid-Flow Machinery (Poland); Wieslaw M. Ostachowicz, The Szewalski Institute of Fluid-Flow Machinery (Poland) and Warsaw Univ. of Technology (Poland)

Various applications of composite materials due to their high strength-to-weight ratios results in an increasing need of studying their mechanical behaviour in case of damage. There are a lot of ENDT and SHM methods dealing with solving the problem. The paper presents a comparative study of three distinct damage detection methods (infrared thermography, neutral axis method based on optical sensors strain measurement and terahertz spectroscopy) for the detection of delamination introduced into a simple GFRP beam-like structure with dimensions 0.35m x 0.05m x 0.003m.

Each of the methods have their own set of advantages and disadvantages. The terahertz spectroscopy is a specialized technique suitable for detecting deterioration inside the structure, but is not suitable for in performance monitoring. Similarly the infrared thermography technique in the active domain may be used for in situ monitoring but not in in-service assessment. Both methods allow the visualization of the internal structure and hence allow identification of the type and the extent of damage. Optical sensors (especially FBG) due to their small diameter and no need of calibration can be permanently integrated within the sample and applied for continuous dynamic strain measurements. The achieved strain is treated as an input for neutral axis (NA) method, which as a damage sensitive feature may be used for in-service monitoring but gives absolutely no information about the type and extent of damage.

The results for damage detection based on proposed comparative studies give a complete description of the analysed structure.

10170-4, Session 1

Shear sensing in bonded composites with cantilever beam microsensors and dual-plane DIC

Jeffery W Baur, AFRL/RXCC (United States); Keith Slinker, Corey Kondash, AFRL/RXCC (United States) and Universal Technology Corporation (United States)

Understanding the shear strain, viscoelastic response, and onset of damage within bonded composites is critical to their design, processing, and reliability. This presentation will discuss the multidisciplinary research conducted which led to the conception, development, and demonstration of a microscale cantilever beam shear sensing within bonded joints. The sensor consists of a single glass fiber cantilever beam with a radially-grown forest of carbon nanotubes (CNTs) within a capillary pore. When deflected, the internal radial CNT array is compressed against an electrode within the pore and the corresponding decrease in electrical resistance is correlated with the external loading. In order to validate sensor performance, a dual plane digital image correlation (DIC) method was developed to separately

measure the strain field on opposing sides of transparent adherends separated by a layer of adhesive in order to spatially quantify the joint shear strain. When this small, simple, and low-cost sensor was non-invasively integrated within a composite bonded joint and cycled in tension, viscoelastic response, and the onset of damage prior to joint failure was observed.

10170-5, Session 2

Full-field ultrasonic inspection for a composite sandwich plate skin-core debonding detection using laser-based ultrasonics

See Yenn Chong, Michael D. Todd, Univ. of California, San Diego (United States)

In this paper, a full-field ultrasonic guided wave method is proposed to inspect a composite honeycomb sandwich specimen made for an aircraft engine acoustic liner. The back skin-core of the specimen is built with two debond defects (diameters of 12.7 mm and 25.4 mm) by subjecting portions of the back skin to high temperatures. A laser ultrasonic interrogation system incorporated with a debonding detection algorithm is developed. The system consists of a 1-kHz laser ultrasonic scanning system and a single fixed ultrasonic sensor to interrogate ultrasonic guided waves in the sandwich specimen. The interest area of 400 mm x 400 mm is scanned at 0.5 mm scan interval. The corresponding full-field ultrasonic data is obtained and generated in three-dimensional (3-D) spatial-temporal domain. Then, the 3-D full-field ultrasonic data is discrete Fourier transformed into 3-D spatial-frequency domain. The ultrasonic frequency responses in two-dimensional spatial are analyzed and the dominant frequency sensitive to the debonding damage is selected. In the algorithm, a continuous wavelet transform based on fast Fourier transform is implemented as a single-frequency bandpass filter to filter the full-field ultrasonic data in 3-D spatial-temporal domain at the selected dominant frequency. As for the results, the debond defects with the diameters of 11 mm and 25 mm were detected, which have good match to the predetermined debond size. For future research, a robust signal processing algorithm and a model-based matched filter will be investigated to make the detection process autonomous and to improve detectability.

10170-6, Session 2

Assessment of damage in 'green' composites

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The behaviour of eco-composites, when subjected to laser or mechanical impact loading, is not well known yet. A research was proposed looking at the behaviour of the 'green' and synthetic composites under impact loading. The study was focused on composites reinforced with short, medium and long fibres. Short fibre composites were made of spruce fibres and ABS. The fibres were used as received and after a thermal treatment. Another set of samples was made of 60 mm-long flax fibres. Two types of thermoplastic polymers were used as matrices: polypropylene and polylactide. Also a woven eco-composite was investigated. It was made of plain woven hemp fabric impregnated with epoxy resin. A fully synthetic woven composite, used as reference laminate, was prepared. It was made of plain woven glass fabric impregnated with epoxy resin and compared to the 'green' composites. Mechanical impacts were performed by means of a falling dart impact testing machine. The specimens were tested at different impact energy levels (from 1J to 5J) by keeping constant the mass of the impactor and varying the drop height. Laser impact tests were performed by means of the high power laser facility. All the samples were tested at six different laser shock intensities, keeping constant the shock diameter and the pulse duration. Six assessment techniques were employed in order to analyse and compare impact damages: eye observation, back face relief, terahertz spectroscopy, laser vibrometry, X-ray micro-tomography and microscopic observations. Different damage detection thresholds for each material and technique were obtained.

10170-7, Session 2

A Constructive Nonlinear Array (CNA) method for complex crack detection in composite materials

Gian Piero Malfense Fierro, Michele Meo, Univ. of Bath (United Kingdom)

Nonlinear ultrasound imaging methods have struggled to compete with standard linear ultrasound methods, such as C-Scan imaging from a phased array system. Currently there are numerous phased array techniques such as Full Matrix Capture (FMC) and Total Focusing Method (TFM) that provide good damage assessment for composite materials. Although, linear methods struggle to evaluate and assess low levels of damage, while nonlinear methods have shown great promise in early damage detection. A sweep evaluation method coupled with a constructive nonlinear array method (CNA) is proposed in order to assess damage specific nonlinearities, address issues with frequency selection when using nonlinear ultrasound imaging techniques and reduce equipment generated nonlinearities. These two methods were evaluated using multiple excitation locations on an impacted composite panel with a complex crack. According to various recent works, damage excitation can be accentuated by exciting at local defect resonance (LDR) frequencies; although these frequencies are not always easily determinable. The sweep methodology uses broadband excitation to determine both local defect and material resonances, by assessing local defect generated nonlinearities using a laser vibrometer it is possible to assess which frequencies excite the complex geometry of the crack. A framework is suggested for correct frequency selection. The dual effect of accurately determining local defect resonances and the reduction of equipment based nonlinearities using CNA result in greater repeatability and clearer nonlinear imaging (NIM).

10170-8, Session 2

SHM of composite laminates via ultrasonic internal resonance

Michele Pasquali, Sapienza Univ. of Rome (Italy); Paolo Gaudenzi, Sapienza Univ. di Roma (Italy)

The study investigates the wave-damage interaction in the frame of ultrasonic structural health monitoring for composite laminates. Attention is drawn on the analysis of the 3D effects associated to the presence of a delamination within the waveguide and affecting the propagation on the pzt-generated diagnostic elastic wave. The interference mechanisms induced by the damage on the internal resonance phenomena which govern the relation between frequency, thickness and phase velocity, are analyzed in the frequency domain. Numerical test show that a modulation of the frequency content of the diagnostic wave takes place when a discontinuity of the propagation path is present.

10170-9, Session 2

Evaluation of adhesively bonded composites by nondestructive techniques

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Composite materials are commonly used in many branches of industry. One method to join or repair CFRP parts is by the use adhesive bonding. There is a search of effective methods for pre-bond assessment of bonded parts and post-bond inspection. Research reported here focuses on post-bond inspection of bonded CFRP plates. In this paper we reported results of two methods. We used noncontact ultrasonic testing (UT) technique as reference method. Ultrasonic testing was made in an immersion tank using phased-array probes. The second method was the electromechanical impedance (EMI). A piezoelectric sensors were surface mounted on each of the samples. Due to piezoelectric effect the electrical response of the sensor is related to mechanical response of the structure to which the sensors is bonded to. Measurements were conducted using HIOKI Impedance Analyzer IM3570. In order to perform a detailed study three samples of each kind were tested. There were three reference samples. The samples with modified adhesive bonds had three levels of severity, so there were three samples with each level of modification. The ultrasonic testing was focused on C-scan analysis taking into consideration the amplitude and time of flight (TOF). Two probes were used, one with 5 MHz frequency, second with 10 MHz. The EMI spectra were gathered up to 5 MHz and they were processed with signal processing algorithms in order to extract differences between reference samples and samples with modified bonds. The UT results provided relevant information about the investigated samples, while the EMI showed sensitivity to the level of adhesive bond modification.

10170-10, Session 3

An adaptive metamaterial beam with hybrid shunting circuits for extremely broadband wave control

Yangyang Chen, Guoliang Huang, Univ. of Missouri (United States)

A great deal of research has been devoted to controlling the dynamic behaviors of phononic crystals and metamaterials by directly tuning the frequency regions and/or widths of their inherent band gaps. Here, we present a novel approach to achieve extremely broadband flexural wave/vibration attenuation based on tunable local resonators made of piezoelectric stacks shunted by hybrid negative capacitance and negative inductance circuits with proof masses attached on a host beam. First, wave dispersion relations of the adaptive metamaterial beam are calculated analytically by using the transfer matrix method. The unique modulus tuning properties induced by the hybrid shunting circuits are then characterized conceptually, from which the frequency dependent modulus tuning curves of the piezoelectric stack located within wave attenuation frequency regions are quantitatively identified. As an example, a flexural wave high-pass band filter with a wave attenuation region from 0 to 23.0 kHz is demonstrated analytically and numerically by using the hybrid shunting circuit, in which the two electric components are connected in series. By changing the connection pattern to be parallel, another super wide wave attenuation region from 13.5 to 73.0 kHz is demonstrated to function as a low-pass filter at a subwavelength scale. The proposed adaptive metamaterial possesses a super wide band gap created both naturally and artificially. Therefore, it can be used for the transient wave mitigation at extremely broadband frequencies such as blast or impact loadings. We envision that the proposed design and approach can open many possibilities in broadband vibration and wave control.

10170-11, Session 3

Experimental observation of wave modulation and Dirac cone in acoustic double zero index metamaterials

Chengzhi Shi, Marc Dubois, Xuefeng Zhu, Yuan Wang, Xiang Zhang, Univ. of California, Berkeley (United States)

Acoustic zero index metamaterials such as density-near-zero metamaterials have received increasing attention due to their potential applications on beam forming, cloaking, wave tunneling, and imaging. High transmission resulted by impedance matching of such zero index metamaterials and surrounding media requires the effective density and inverse bulk modulus to be simultaneously zero. Metamaterials possessing this property are called double zero index metamaterials. The design of double zero index metamaterials needs scatterers with sound speed lower than the background medium, which is extremely challenging for air acoustics because the air sound speed is among the lowest. This challenge can be solved for high order waveguide mode by designing structures with larger thickness. An experimental scan of the pressure field inside our design metamaterial excited by a point source reveals the existence of a Dirac cone at the Brillouin zone center. The measured envelope of the propagating wave inside the metamaterial shows double negative, double positive, and double zero properties below, above, and at the Dirac point,respectively. This result is confirmed by the measured acoustic beam out of the metamaterial. A gapless transition between double negative and double positive acoustic metamaterials is realized. The development of this double zero index metamaterial provides new routes to broaden practical applications of acoustic metamaterials.

10170-12, Session 3

Experimental verification of topological band-transition in one-dimensional phononic crystals

Rajesh Chaunsali, Aman R. Thakkar, Jinkyu Yang, Univ. of Washington (United States)

Phononic crystal is a periodic arrangement of structural constituents capable of filtering a specific frequency range of elastic waves propagating in the medium. It is recent that the topological characterization of such phononic crystals has enabled researchers to see them in new light. Two phononic systems showing similar band-gaps can still be different on topological grounds. This difference is mathematically quantified in terms of their topological invariants. From the viewpoint of fundamental physics, the difference manifests as special boundary/surface modes in topologically non-trivial systems. Such modes are 'topologically protected' in a sense that small impurities/defects near the boundaries/surfaces do not affect their presence.

In this study, we present the most fundamental of such topological phenomena using a one-dimensional phononic crystal. Our system consists of a set of identical cylinders interacting as per Hertz's contact law aligned as a pre-compressed chain. Inter-particle stiffness can be changed by altering the contact angles between cylinders. In this way, the system offers remarkable flexibility in term of in-situ tuning of stiffness distribution along the chain. Inspired by Su-Schrieffer-Heeger dimer model, our system has two contact angles alternating along the chain. We fix one contact angle at $\alpha 1$ and vary the other angle $\alpha 2$. We numerically demonstrate and experimentally verify that the change in angle $\alpha 2$ results in topological transition in the system. Moreover, this topological transition is accompanied by the emergence of a robust boundary mode in the system. We envision that such tunable system can pave the way for designing novel engineering

systems for energy harvesting/isolation purposes relying on robust surface vibrational characteristics.

10170-13, Session 3

A disorder-based strategy for tunable, broadband wave attenuation

Paolo Celli, Weiting Zhang, Davide Cardella, Stefano Gonella, Univ. of Minnesota (United States)

One of the most daunting limitations of phononic crystals and acoustic/elastic metamaterials is their passivity: a given configuration is bound to display its phononic properties only around its design point, i.e., working at some pre-determined operating conditions. In the past decade, this shortcoming has inspired the design of phononic media with tunable wave characteristics; noteworthy results have been obtained through a family of methodologies involving shunted piezoelectric internal elements. Shunting a piezoelectric element means connecting it to a passive electric circuit; tunability stems from the ability to modify the effective mechanical properties of the piezoelectric medium by modifying the circuit characteristics. One of the most popular shunting circuits is the resistor-inductor (RL) circuit, which behaves as an electrical resonator. A common motif among the works employing shunted piezos for phononic control is periodicity: the patches are typically periodically placed in the domain and the circuits are identically tuned.

The objective of this work is to demonstrate that the wave attenuation performance of structures with shunted piezoelectric patches can be improved by leveraging notions of organized disorder. We discuss a strategy based on the idea of rainbow trapping---broadband wave attenuation obtained by tuning an array of resonators at distinct neighboring frequencies. Based on this concept, we design and test an electromechanical waveguide structure capable of attenuating waves over broad frequency ranges. In order to emphasize the fact that periodicity is not a binding requirement when working with RL shunts (which induce locally resonant bandgaps), we report the performance of random arrangements of patches. In an attempt to demonstrate the tunability attribute of our strategy, we take advantage of the reconfigurability of the circuits to show how a single waveguide can attenuate waves over different frequency ranges.

10170-14, Session 3

Controllable wave propagation of hybrid dispersive medium with LC high-pass network

Edgar Flores Parra, ETH Zürich (Switzerland); Andrea E. Bergamini, EMPA (Switzerland); Paolo Ermanni, ETH Zürich (Switzerland)

This work reports on the wave transmission characteristics of a hybrid one dimensional (1D) medium. The hybrid characteristic is the result of the coupling between a mechanical waveguide in the form of an elastic beam, and an electrical network. The network configuration investigated is an LC high-pass, consisting of a series of capacitors connected in series through grounded inductors. The capacitors correspond to a periodic array of piezoelectric patches that are bonded to the beam thus coupling the two waveguides. The coupling is characterized by a coincidence frequency/wavenumber corresponding to the intersection of the dispersion curves. At this coincidence frequency, the hybrid medium features attenuation of wave motion as a result of the energy transfer to the electrical network. This energy exchange is depicted in the dispersion by eigenvalue crossing, a particular case of eigenvalue veering. This paper presents the numerical investigations of the wave propagation in the considered medium, and validates the numerical findings with experimental evidence of the wave transmission characteristics. Moreover, the dispersion properties of the electrical network are further studied by varying the inductances thus exploiting the tunability of the periodic electrical domain, i.e: monoatomic and diatmomic unit cell configurations. The LC high-pass network offers several advantages over other configurations, from ease of implementation as the piezoelectric elements are not grounded, to a smaller inductance values to achieve attenuation at a given frequency. Such media could be interfaced with more complex electrical networks to create a new type of smart materials.

10170-15, Session 3

Origami-based mechanical metamaterials with tunable frequency band structures

Hiromi Yasuda, Riley Pratt, Jinkyu Yang, Univ. of Washington (United States)

We investigate wave dynamics in origami-based mechanical metamaterials composed of bellows-like origami structures, specifically the Tachi-Miura Polyhedron (TMP). One of the unique features of the TMP is that its structural deformations take place only along the crease lines, therefore the structure can be made of rigid plates and hinges. By utilizing this feature, we introduce linear torsional springs to model the crease lines and derive the force and displacement relationship of the TMP structure along the longitudinal direction. Our analysis shows strain softening/hardening behaviors in compression/tensile regions respectively, and the force-displacement curve can be manipulated by altering the initial configuration of the TMP (e.g., the initial folding angle). We also fabricate physical prototypes and measure the force-displacement behavior to verify our analytical model. Based on this static analysis on the TMP, we simplify the TMP structure into a linkage model, preserving the tunable strain softening/hardening behaviors. Dynamic analysis is also conducted numerically to analyze the frequency response of the simplified TMP unit cell under harmonic excitations. The simplified TMP exhibits a transition between linear and nonlinear behaviors, which depends on the amplitude of the excitation and the initial configuration. In addition, we design a 1D system composed of simplified TMP unit cells and analyze the relationship between frequency and wave number. If two different configurations of the unit cell (e.g., different initial folding angles) are connected in an alternating arrangement, the system develops frequency bandgaps. These unique static/dynamic behaviors can be exploited to design engineering devices which can handle vibrations and impact in an efficient manner.

10170-16, Session 3

Flexible metamaterials for shape-adaption acoustic manipulation

Hongkuan Zhang, Yong Cheng, Shanshan Yao, Xiaoming Zhou, Gengkai Hu, Beijing Institute of Technology (China)

Acoustic hyperlens relying on the hyperbolic dispersion has shown the ability to image objects with the resolution beyond the diffraction limit. The formation of acoustic hyperbolic dispersion is based on the anisotropic-mass behavior in structured metamaterials, which are previously rigid in order for the absolute leakage-free guidance of sounds. For example, acoustic hyperlenses have been constructed with a cluster of straight rigid channels for either near-field or far-field super-resolution imaging. However, the rigid hyperlens lacks in the ability of easy deformation necessary for shape conforming to the object under detection. In addition, the rigid nature leaves the magnifying hyperlens being only in the cylindrical conformation. In this work, we propose to make acoustic channels flexible and readily deformed to achieve the shape-adaption capability for metamaterials. As an example of illustrating the idea, acoustic flexible hyperlens for shape-adaption magnifying imaging will be experimentally studied. The proposed hyperlens is fabricated by equal-length soft plastic tubes. Experiment results show that acoustic transmission spectrum of a single tube is unchanged against its bending deformation. As a result, a planar magnifying hyperlens can be practically realized and its imaging performance has been experimentally verified. It is further found that the imaging quality is stable when the input surface of lens is curved, firmly demonstrating the shape-adaption ability of the flexible hyperlens. The soft-tube acoustics can improve a variety of channel-structured metamaterials by equipping them the flexible and shape-adaption abilities, opening then a new degree of freedom for full control of sound.

10170-128, Session 3

Simultaneous fatigue-life extension and crack monitoring of damaged steel structures using multifunctional carbon nanotube-based composites

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Steel structures including bridges are susceptible to cracking, particularly due to fatigue-sensitive details found in older designs. Therefore, one of the major challenges to keep those steel bridges in service is to rehabilitate existing and potential fatigue damage. There are several conventional approaches to extend the fatigue-life of damaged steel structures, e.g., drilling a crack stop-hole to reduce the stress concentration at the crack tip as well as welding and bolting of steel plates or adhesive-bonding of fiber-reinforced polymers (FRP) to reduce the overall stresses. Improvement in material properties of FRP and adhesives make them a viable candidate to apply for extending the fatigue-life of steel structures. However, drawbacks include the potential for debonding in the adhesive layer and/or interfaces between adhesive and adherents as well as difficulty in monitoring fatigue crack growth after rehabilitation. In this research, a holistic approach has been proposed and evaluated for simultaneous extension of fatigue-life and monitoring by integrating carbon nanotube (CNT)-based sensing layers in adhesive-bonded FRP. CNT-based sensing layers have a nerve-like electric resistance network, which enables distributed sensing capabilities to monitor stress levels, crack growth, and damage progression. Using laboratory-scale experiments, the simultaneous fatigue-life extension and crack monitoring capability of multifunctional CNT-based composites has been evaluated. This paper introduces the fundamental concept of integrated fatigue-rehabilitation and monitoring of steel members, presents a laboratory-scale experiment to demonstrate the feasibility and effectiveness, and discusses challenges for implementation in real structures.

10170-500, Session Plen

Predictive simulation of structural health monitoring

Victor Giurgiutiu, Univ. of South Carolina (United States)

Predictive simulation of the structural health monitoring (SHM) process has a crucial role in the efficient design of effective SHM systems. Predictive simulation is part of the forward problem which calculates the sensor signals that would be recorded for a given structural state and a given excitation. The inverse problem, which is more difficult, has to estimate the structural state from known excitation and known measured signals. This inverse problem is usually solved through an optimization process in which the forward problem is run repeatedly for many times. A fast and accurate forward problem that has adequate sensitivity to damage presence while being insensitive to confounding factors is highly desirable for an efficient solution of the inverse problem. Several examples derived from work performed in the laboratory for active materials and smart structures (LAMSS) of the University of South Carolina, USA will be presented and discussed. The presentation will end with conclusions and suggestions for future work.

10170-18, Session 4

Control of subwavelength flexural waves via kirigami-based hyperlens

Rui Zhu, Hiromi Yasuda, Univ. of Washington (United States); Guoliang Huang, Univ. of Missouri (United States); Jinkyu Yang, Univ. of Washington (United States)

In this presentation, we propose a novel design of elastic metamaterial that possesses unique anisotropic mass density and hyperbolic dispersion, which enables subwavelength-scale flexural wave manipulation. The metamaterial unit cell is inspired by kirigami, an ancient art of paper cutting and folding. A three-dimensional kirigami microstructure can be obtained by simply cutting and folding a thin metallic plate. By attaching the resonant kirigami microstructures periodically on the top of a host plate, a hyperbolic metamaterial plate can be manufactured without any perforation that degrades the strength of the pristine plate. A theoretical model based on the classic plate theory and mass-spring model is developed to understand the working mechanism of the elastic metamaterial. Dispersion curves are obtained by using an extended plane wave expansion method. An anisotropic effective mass density tensor is retrieved based on effective medium theory, which explains the different couplings between the local resonance of kirigami microstructure and the global flexural wave propagations in the host plate along two in-plane principal directions. Finally, numerical simulation on an elastic hyperlens is conducted to demonstrate the subwavelength-scale flexural wave control and super-resolution imaging abilities. The advantages of the proposed kirigami-based elastic hyperbolic metamaterial are twofold: (i) simple manufacturing process without perforation in the pristine plate and (ii) subwavelength flexural wave manipulation providing a high signal-to-noise ratio in plate-like engineering structures. Therefore, the proposed elastic hyperbolic metamaterial could be highly promising for high resolution damage imaging in nondestructive evaluation and structural health monitoring.

10170-19, Session 4

Tunable digital metamaterial for control of elastic wave propagation

Ziwei Wang, Kai Zhang, Beijing Institute of Technology (China)

Elastic metamaterials have received extensive attention in science and engineering fields. Traditional metamaterials only operate at fixed frequency ranges, narrowing the application in limited situations. In this paper, a tunable digital metamaterial is proposed for control of elastic waves at low frequency. The primary frame and auxiliary beams are fabricated using 3D printing technology, and each cell is embedded with two electromagnets. Switching electromagnets between detaching and attaching modes will change the resonant frequency of the local resonator. A band gap at low frequency will appear or disappear depending on electromagnets status. Different waveguides are programmable in the metamaterial and can be switched instantly in the experiment, showing the well control ability of elastic waves. To reveal the underlying mechanism, a tunable 1D spring-mass system is proposed and investigated both theoretically and experimentally. The passing and stopping effect of the cell with electromagnets in different states shows the potential for a digital metamaterial, mimicking 1 and 0 bits in digital technology. Sequencing 1 and 0 bits in the supercell with proposed coding rules allows programmable broadening of the band gap of the metamaterial. This metamaterial can act as a coating layer enhancing wave manipulation ability of flexible structures, or as an intelligent device with energy harvesting and self-powering features, providing new ways for elastic wave control in engineering fields.

10170-20, Session 4

Isotropic transformation acoustics and applications

Andrew Norris, Xiaoshi Su, Rutgers, The State Univ. of New Jersey (United States)

Transformation acoustics (TA) offers the acoustical designer the potential to alter sound propagation in an exact manner that satisfies the wave equation regardless of frequency, high or low. This is the reason why TA is the foundation for exotic effects such as acoustic cloaking, which requires material properties that are anisotropic but difficult to realize in practice. This talk will focus on the special case of isotropic TA and its applications. The motivation for focusing on isotropic TA is that materials with the required properties can be readily realized by a wide variety of homogenized structures. We concentrate on underwater acoustic devices and show that quasi-phononic structures with unit cells comprising circular, square and other shaped cylinders in water provide the range of required properties. We first show that isotropic TA devices require only a change in effective bulk modulus, but not density. Two implications are explored: first, the ability of conformal mappings to yield highly accurate focusing lenses is described. These devices act, by reciprocity, as monopole to highly one-way-wave radiators. Second, the fact that any TA device must match to the exterior fluid places constraints that are explored. A class of a focusing devices is described that are optimally matched in both impedance and focusing. Numerical examples and data from experimental measurements demonstrate these ideas.

10170-21, Session 4

Space-time modulations of inner-resonant metamaterials

Hussein Nassar, Univ. of Missouri (United States); Andrew Norris, Rutgers, The State Univ. of New Jersey (United States); Guoliang Huang, Univ. of Missouri (United States)

When a set of resonators is attached to a master structure, a bandgap opens in the vicinity of the resonance frequency. Then, using piezoelectric circuitry for instance, the spring constant coupling the resonators to the structure can be tuned thus allowing to actively control the resonance frequency and subsequently the position of the bandgap. In this study, we investigate the consequences of dynamically changing the resonance frequency of a resonant metamaterial on its dispersion diagram. In particular, the resonance frequency is modulated periodically in space and in time at a uniform speed in a wave-like fashion and at low frequencies of the same order of magnitude of the resonance frequency itself. A two-scale asymptotic homogenization approach shows that the modulated resonant metamaterial effectively behave as another resonant metamaterial with a different set of resonance frequencies. Changing the modulation speed reveals interesting effective dynamics whereby the bandgaps of the original metamaterial split, move, condense and merge to form new band structures. The results are illustrated and exemplified through the analytical study of a onedimensional elastic medium coupled with a continuous distribution of spring-mass oscillators resonating at low frequencies. The conclusions point towards possible applications in breaking time-reversal symmetry, active wave control and filtering.

10170-22, Session 5

Parametric studies for semi-analytical modal analysis of plate-mounted resonators

Christoph Schaal, California State Univ., Northridge (United States); Robert M'Closkey, Ajit K. Mal, Univ. of California, Los Angeles (United States)

Damping in miniature resonators is a consequence of many factors, one of which is due to interaction with the substrate to which the resonator is mounted. It is common practice to create a model of the resonator that includes a small segment of the substrate plate with a finite element (FE) software in conjunction with absorbing boundary elements. As an alternative to implementing absorbing boundary elements, semi-analytical methods have been developed in which such elements are replaced by analytical expressions for Lamb waves. This approach typically requires the specification of a harmonic load and the determination of the subsequent harmonic response at a point on the resonator. The modal frequency and damping can then be estimated from the computation of the frequency response function on a frequency grid. In this paper, it is shown how the standard semi-analytical approach can be extended to a modal analysis paradigm. This more fundamental analysis of the plate-resonator system permits the direct determination of the quality factors associated with the resonator modes without recourse to steady-state harmonic analysis. The modal analysis approach is demonstrated for single and double cantilever configurations on a plate in the case of plain strain. The influence of the number of selected Lamb modes, mesh density and the size of the modeled plate segment is investigated through parametric studies. Moreover, it is shown that the modal analysis results are in good agreement with the time harmonic semi-analytical method and conventional transient finite element simulations.

10170-23, Session 5

Application of distributed point source method (DPSM) to wave propagation in anisotropic media

Samaneh Fooladi, Tribikram Kundu, The Univ. of Arizona (United States)

Distributed Point Source Method (DPSM) has been developed by Placko and Kundu in 2001, as a technique for modeling wave propagation problems. DPSM can be used for modeling ultrasonic, electrostatic and electromagnetic fields scattered by defects and anomalies in a structure. The modeling of such scattered field helps to extract valuable information about the location and type of defects. Therefore, DPSM can be used as an effective tool for Non-Destructive Testing (NDT).

While DPSM has been successfully used for isotropic materials in literature, its application to anisotropic media has not been developed yet. Anisotropy adds to the complexity of the problem, both mathematically and computationally. Computation of the Green's function which is used as the fundamental solution in DPSM is considerably more intense for anisotropic media, and it cannot be reduced to closed-form solution as is done for isotropic materials.

The purpose of this study is to investigate and implement DPSM for an anisotropic medium. While the mathematical formulation and the numerical algorithm will be considered for general anisotropic media, more emphasis will be placed on transversely isotropic materials in the numerical examples. The unidirectional fiber-reinforced composites which are widely used in today's industry are good examples of transversely isotropic materials. Development of an effective and accurate NDT method can be of paramount importance for in-service monitoring of damage in composite structures.

10170-24, Session 5

Computational wave field modeling in anisotropic plate

Sajan Shrestha, Sourav Banerjee, University of South Carolina (United States)

In this paper, the wave field has been computationally modeled in the anisotropic plate. The Christoffel's equation is solved to calculate the phase velocity of different wavefronts present at any point in the problem geometry. The calculated phase velocity is then used to develop the Green's

function. The anisotropic Green's function was developed by implementing Radon transform and Spectral theorem into governing elastodynamic equation. Then the wave behavior in the anisotropic plate is simulated and studied by instigating the calculated Green's function into the computational non-destructive evaluation (CNDE) technique, distributed point source method(DPSM). The wave propagation with different actuation angles for the transducer are simulated in plate with various forms of anisotropy such as transversely isotropic, orthotropic, monoclinic and fully anisotropic plate. The study was performed such that the different anisotropic wave behaviors can be understood to the maximum extent in simplest form. The actuation angles used were 0, 30, 45, 60, 90 and the critical angle from the perpendicular to problem geometry surface. MATLAB is used for coding and simulation.

10170-25, Session 5

Optimization of multi-scale modelling of CNT/polymer composite strain sensors

Krzysztof Grabowski, Wieslaw J. Staszewski, Tadeusz Uhl, Pawel Packo, AGH Univ. of Science and Technology (Poland)

Carbon nanotube-based composites have been deeply investigated in the recent years. CNTs due to their unique physical properties have been proposed for various applications in different disciplines of science and engineering. Due to the remarkable electrical conductivity of CNTs, one of practical applications is related to the development of strain sensing smart coatings. Up to date high sensitivity strain sensors for micro- and macro-scale applications were proposed. However, their repeatability is still a chalenging issue.

In order to facilitate the design process and to investigate multidomain relationships for sensor's parameteras and its properties numerical models and simulations of such structures have been cerried out with the primary focus on investigation of electrical conductivity for various concentrations of CNTs within the composite. More accurate and detailed studies include analysis of the influence of deformation on changes in conductivity. However, due to significant microstructural complexity of the system (i.e. large number of CNTs within the structure) multiscale modelling and analysis approach must be employed.

The main objective of this paper is to outline an optimization framework and guidelines for a multiscale electro-mechanical model based on the Representative Volume Element (RVE) concept for a carbon nanotubes-based sensor. The device utilizes change in electrical conductivity of a nanocomposite under applied deformation. The optimization strategy allows for investigation of various micro-scale model parameters (e.g. size of an RVE, CNTs parameters etc.), their influence on the macro scale model, and their adjustment. Model paremeters convergence studies are perfomed for different geometrical properties of CNTs and for various sizes of RVEs - revealing their critical mutual relationships. Also, the impact of boundary conditions at the micro-scale RVE structure is discussed.

10170-26, Session 5

Peridynamic modeling for displacement computation around an interfacial crack in a bimaterial thin plate

Mohammad Hadi Hafezi, The Univ. of Arizona (United States); Reza Alebrahim, National Univ. of Malaysia (Malaysia); Tribikram Kundu, The Univ. of Arizona (United States)

William's problem in classical fracture mechanics is well-known. Stress and displacement fields near a crack tip in a linear elastic homogeneous material computed by William's method have been accepted by the research community. However, direct extension of William's method to an interface crack located at the interface of two linear elastic materials gives unrealistic oscillating singularity and hence has not been accepted by the research community. In this investigation, the solution is developed for a bi-material plate with a crack at the interface. The displacement field around an interfacial crack in a thin bi-material plate is simulated using peridynamic theory. The specimen is loaded by remote shear loading. A computer program was developed to implement bond based peridynamic modeling in a bi-material thin plate. The simulation results are found to be in good agreement with published experimental results.

10170-27, Session 6

Dual-frequency transducer with a wideband PVDF receiver for contrast-enhanced, adjustable harmonic imaging

Jinwook Kim, North Carolina State Univ. (United States); Brooks D. Lindsey, The Univ. of North Carolina at Chapel Hill (United States) and North Carolina State Univ. (United States); Sibo Li, North Carolina State Univ. (United States); Paul A. Dayton, The Univ. of North Carolina at Chapel Hill (United States) and North Carolina State Univ. (United States); Xiaoning Jiang, North Carolina State Univ. (United States) and City Univ. of Hong Kong (China)

Acoustic angiography is a contrast-enhanced, superharmonic microvascular imaging method. This imaging method has shown the capability of high resolution and high contrast-to-noise-ratio (CNR) for imaging microvasculature in developing tumors. Dual-frequency ultrasound transducers are used for this new imaging technique in order to excite microbubble contrast agent (MCA) at a low frequency close to resonance (1-5 MHz) while receiving only harmonic signals from microbubbles at a higher frequency (>10 MHz). The main challenge with conventional dual-frequency transducers is limited penetration depth due to insufficient receiving sensitivity for high-frequency harmonic signal detection. We hypothesize that a receiver with a high receiving sensitivity spanning a wide superharmonic frequency range (3rd to 6th) enables selectable bubble harmonic detection considering the required penetration depth. Here, we develop a new dual-frequency transducer composed of a 2 MHz piezocomposite transmitter and a wideband polyvinylidene fluoride (PVDF) receiver for adjustable harmonic imaging at a given penetration depth. The developed transducer was tested by measuring the harmonic response (2nd to 7th harmonics) from a microbubbles injected in a 200 ?m-diameter vessel-mimicking tube (positioned at a depth of 45 mm). Band pass filters having pass bands of 2 MHz (e.g. 5 to 7, 7 to 9 MHz, etc) from 1 to 15 MHz were used to compare CNR of individual harmonics. Despite the long imaging distance, the prototype transducer detected clear harmonic response up to 5th harmonics (CNR>16 dB), which is higher than our previous result. This transducer shows a feasibility of adjustable harmonic imaging with various penetration depth.

10170-28, Session 6

Peridynamic modelling of fracture in human vertebrae

Mohammad Hadi Hafezi, The Univ. of Arizona (United States); Reza Alebrahim, National Univ. of Malaysia (Malaysia); Tribikram Kundu, The Univ. of Arizona (United States)

Vertebral fracture can be initiated through failure of trabecular bone under high compressive loading. This phenomenon can cause back pain, deformity, loss of weight and many other back problems. This study provides a peridynamic modelling of vertebral fracture. Bond-based peridynamic method was followed to model a human lumber spine vertebra under

high impact loading. The composing elements of the bone matrix, Cortical and Cancellous, were considered in the peridynamic simulation. Moving force with a specified velocity was applied to peridynamic nodes on the surface to simulate impact loading. Computed results are compared with those available in the literature. It is investigated how peridynamic model predictions compare with finite element generated results.

10170-29, Session 6

Birefringence Fourier transform spectrometer

Wei-Chih Wang, Univ. of Washington (United States) and National Tsing Hua Univ. (Taiwan); Peng Jyun Chen, National Tsing Hua Univ. (Taiwan)

Fourier transform spectrometer (FTS) is a fundamental analytical tool applied to a wide range of situations such as chemical, biological analysis applications and environmental monitoring. The main technique of the design is interferometer that allows lower frequency equipment to use to measure higher frequency signal and Fourier transform is used to allow to analyze multiple wavelengths signal simultaneously such as an impulse response. The aim of this design is to create a simple compact FTS to measure greater than 0.1nm resolution with a wide range of spectrum generated directly from interferogram by FFT and using birefringent effect. The birefringent interference is formed when incident wave is introduced in such that both Ordinary and Extraordinary waves are excited and observed at the output by passing light through a wave plate polarizers system. The spectral resolution of the FTS depends on the maximum possible optical path difference (OPD) is achieved by the newly proposed wave plate design

10170-30, Session 6

Design, analysis, and fabrication of a piezoelectric force tray for total knee replacements

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Total knee replacements (TKR) represent over 700,000 surgeries in the United States alone and more than 70,000 in England and Wales every year. This surgery becomes a priority when the articular cartilage of the knee becomes damaged or worn out and the level of pain is unbearable for the patient. Today, thanks to sensor assisted TKR, patient satisfaction of 97% is reported in the literature for 1 year period after surgery. The most common reasons for knee failure are infection, loosening, and instability. It has been reported that about 25% of revision knee arthroplasties can be avoided using proper ligamentous balance. Today, despite the improvements in surgery techniques, TKR is still mostly based on surgeon "feel" and the balance is not well quantified. This work investigates the design of a piezoelectric sensing system for TKR. Several simplified designs of instrumented ultra-high molecular weight polyethylene (UHMW) bearing plates with various arrangements of piezoelectric transducers are investigated. The proposed models strategically place multiple piezoelectric transducers in order to sense the medial and lateral forces applied on the UHMW bearing as well as the location of the contact points. The relationship between the applied forces and the contact points, and the voltage output of the piezoelectric elements is analytically established. Using finite element analysis (FEA), the effects of dimensional parameters are explored to find the optimized pattern of piezoelectric elements with the minimum error in force sensing performance. Finally, experimental studies are conducted to investigate the validity of performed FEA.

10170-31, Session 6

Air-coupled acoustic radiation force source for non-contact measurement of soft media elasticity

Lukasz Ambroziński, AGH Univ. of Science and Technology (Poland) and Univ. of Washington (United States); Ivan M. Pelivanov, Univ. of Washington (United States) and M.V. Lomonosov Moscow SU (Russian Federation); Shaozhen Song, Soon Joon Yoon, David S. Li, Liang Gao, Univ. of Washington (United States); Tueng T. Shen, Univ. of Washington (United States) and Univ. of Washington (United States); Ruikang K. Wang, Matthew O'Donnell, Univ. of Washington (United States)

Acoustic radiation force (ARF) is commonly used in ultrasound (US)-based elastography to generate shear waves deep within soft tissue. These waves can be detected with different methods, e.g. contact conventional ultrasound imaging probes or contact free magnetic resonance or optical coherence tomography (OCT). For many clinical applications, however, for instance the eye, a totally non-contact system for generation/detection of mechanical waves is needed.

Here, we present a method for efficient non-contact excitation of broadband transverse mechanical waves in soft media. The approach is based on pushing the medium under study with a 1 MHz chirped US wave focused to its surface from air. The US beam reflected from the air/medium interface provides the ARF force to the medium surface launching a transient mechanical wave in the transverse (lateral) direction.

The design and performance of the air-coupled transducer is discussed. The focal zone, peak pressure and acoustic intensity are measured for transducers with different numerical apertures. Time and frequency characteristics of the propagating mechanical waves, generated in soft tissue, are tracked with a phase-sensitive ultra-fast frame rate OCT imaging system. Application of the proposed method for non-contact, non-invasive, sub-mm resolution elasticity measurement in soft tissue is proposed.

10170-32, Session 6

Peridynamic theory for medical applications

Mohammad Hadi Hafezi, The Univ. of Arizona (United States); Reza Alebrahim, National Univ. of Malaysia (Malaysia); Tribikram Kundu, The Univ. of Arizona (United States)

Tissue-needle interaction model in medical applications is investigated using new computational tool called Peridynamics. Active needle has two parts (i) cannula and (ii) nitinol wires. We take into account the actuation forces from shape memory alloy while others typically simplified this modeling by replacing shape memory alloy generated forces by magnetic forces. This is the distinctive feature of our Peridynamic modeling when compared with current finite element based models where magnetic forces simulate the actuation forces generated by shape memory alloy. This is not true for surgical needles. The objective of this investigation is to predict the deflection of the needle tip when it reaches some target location in a body. Simulations are done for different needle diameters and insertion forces. The optimum design has been validated with needle insertion experiments.

10170-33, Session 6

Resonant frequencies of quasi-brittle materials with sacrificial bonds and hidden lengths

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The mechanical response, in particular the failure mode, of quasi-brittle materials such as bone, engineered lattice structures, and certain polymeric composites is quite different from that of conventional materials. For example, in the case of bone and engineered lattice structures, it is hypothesized that Sacrificial Bonds and Hidden Length (SBHL) polymeric chains in structural molecules provide a mechanism for energy dissipation, which ultimately leads to enhanced strength. A detailed understanding of mechanics of failure and the mechanisms for enhanced strength of these systems is necessary for developing efficient health monitoring strategies. With this as the motivation, we study dynamic response as captured by resonant modes of vibration for the aforementioned systems. Numerical simulations are carried out to the quantify influence of SBHL parameters (e.g., contour length of fibril-polymers, length of hidden loops, density of fibril-polymers, elastic modulus of polymeric chains, and number of SBHLs in a polymer chain) on resonant frequency characteristics. In particular, we discuss how these characteristics change as these systems approach failure limit. Finally, we obtain a simple reduced-order model relating resonant frequencies and SBHL parameters with potential applications to Resonant Ultrasound Spectroscopy.

10170-34, Session 6

Human-based pattern recognition framework for data-driven structural health monitoring utilizing hearing receptors

Shervin Khazaeli, Ashutosh Bagchi, Concordia Univ. (Canada); Adam S. Ziabari, McGill Univ. (Canada)

In the context of data-driven based Structural Health Monitoring (SHM), damage detection techniques have been vastly utilized to reveal the probable induced damages in an instrumented structure without necessitating the mathematical modelling of the structure. In this regard, based on the training and testing scheme, pattern recognition algorithms have been developed according to supervised and unsupervised learning. Inspired by new advances in neuroscience, this work aims to utilize the human brain for supervised pattern recognition purposes, in which prior knowledge of the state of the structure (i.e. undamaged or damaged) is available. To this end, a framework is developed and implemented for such damage detection in a shear-building structure exposed to different damage scenarios. Here, human ears are used as receptors in order to feed the brain. Various sets of response time series of the structure are transformed into two audio signals corresponding to the original and its cepstrum signals. Subjects (humans) are exposed to induced audible signals by a consistent training. The ability of the human to determine the state of the structure is examined by test sets of responses (i.e. training-test scheme). Finally, the results are compared with those obtained with the aid of specific Machine Learning (ML) algorithms. Initial results have shown that such assessment has a potential huge impact on understanding the structural behavior by involving the human perception directly. Moreover, such study can further be exploited to use other receptors, particularly touch receptors as a mean to transfer data into the brain via vibrotactile patterns.

10170-110, Session PMon

Fatigue crack monitoring of aerospace structure based on binary tree support vector machines

Shenbo Lu, Zhou Li, Nanjing Univ. of Aeronautics and Astronautics (China)

Aerospace structures are often subjected to a variety of loads at the stress concentration area. These areas are easily to produce fatigue crack that is not visible. The methods used currently for damage detection, such as ultrasonic scanning, acoustic emission, require the structure be taken out of service. Also, overweight detection system and expensive cost make it unrealistic to monitor the aircraft in real time. In order to overcome the difficulties on the identification of fatigue in aerospace structure, this paper has done some research on the algorithm of damage identification and methods of signal processing. A novel method combines multi-class classification method based on binary tree support vector machines (BT-SVM) with matching pursuit (MP) method is developed. In this method, Lamb wave is decomposed into a linear combination of several Chirplet atoms by MP method, and the matching parameters are extracted as feature vectors to train and test in BT-SVM classification algorithm. Then one simulation of lug joint is carried out for studying the effect of crack extension on Lamb wave signals propagation. The research shows that the attenuation of received Lamb wave signals is becoming more and more serious with the increasing of crack length. This phenomenon lays the foundation for the following experiment research. Finally, fatigue loading experiments are carried out in lug joints. The results show that this new method can monitor the length of fatigue crack effectively.

10170-111, Session PMon

Non-destructive monitoring of a prestressed bridge with data-driven methods

Maria Pina Limongelli, Mattia Tirone, Politecnico di Milano (Italy); Cecilia Surace, Politecnico di Torino (Italy)

Non-destructive vibration based methods can be used as diagnostic tool to identify damage in structures. Periodic inspections or permanent monitoring networks of sensors can indicate the emergence of possible damage occurring during the structure lifetime. One of the intrinsic drawbacks in the use of dynamic parameters for damage identification purposes lies in their small sensitivity to damage and in the sensitivity of some of them (e.g. modal frequencies) to environmental changes such as temperature or operational conditions.

Several method have been proposed in literature for damage identification purposes. Some of them allow detecting the existence of damage, others provide information about its location as well.

Data driven method localize damage based on responses recorded on the structure without the need of a Finite Element model. Many of these methods are based on the detection of irregularities in the deformed shape of the structure: modal or operational shapes have been proposed to this purpose by different authors. The reliability of the methods proposed in literature is often verified on numerical models that, by their nature, cannot reproduce all the sources of uncertainties - environmental, operational, experimental - that affect responses recorded of the structure. The availability of data recorded on real structures provides precious material for the check of damage identification methods.

In this paper the performance of several data-driven methods for damage localization is investigated and compared with reference to the case of a prestressed concrete road bridge, the S101 Bridge in Austria. The bridge, built in the early 1960, is a typical example of a European highway bridge. Responses to ambient vibration have been recorded both in the undamaged and in several different damage scenarios artificially introduced on the bridge. Damage was introduced by lowering one of the bridge piers and by

cutting prestressing tendons of one beam of the bridge deck. The sensitivity of the different methods is discussed with respect to the type and severity of the damage scenarios.

10170-112, Session PMon

Concrete surface strain develop progress monitoring of nuclear power plant containment vessel during the containment test using fiber optic sensors

Kaixing Liao, Suzhou Nuclear Power Research Institute, China General Nuclear Power Corp. (China); Jinke Li, Dalian Univ. of Technology (China); Xianglong Kong, Suzhou Nuclear Power Research Institute, China General Nuclear Power Corp. (China); Changsen Sun, Xuefeng Zhao, Dalian Univ. of Technology (China)

After years of operation, the safety of the concrete structure of Nuclear Power Plant(NPP) is an important aspect. In order to detect the degradation in strength and the structure deformation, several sensors such as vibrating wire strain gauge, invar wires and pendulums, are used in NPP. However, the amounts of sensors above is limited due to the cost. Besides, many surface defects still needs manual work thus the efficiency is relatively low. Due to the well durability of fiber optic sensors, three kinds of fiber optic sensors are chosen to use in the NPP to monitor the containment test. The three kinds of fiber optic sensors which have their own advantages and disadvantages are white-light interferometry(WLI), Brillouin optical-fiber time-domain analysis(BOTDA) and Fiber Bragg grating(FBG). These sensors are installed on the surface of concrete of the containment vessel to monitor the strain change. According to the measuring result, the fiber optic sensors can monitor the strain change during the containment test. After the containment test, some place's strain of the containment vessel is recoverable, while some place is unrecoverable. The unrecoverable strain should be paid close attention to because the deformation there is nonlinearity and easy to go on. Apart from these, if BOTDA is widely used in the NPP, the surface defects are easier to detect than manual work. As a consequence, the three fiber optic sensors have good potential in the structure health monitoring of NPP.

10170-113, Session PMon

In-situ control of topological dynamics in one-dimensional dimer systems

Aman R. Thakkar, Rajesh Chaunsali, Jinkyu Yang, Univ. of Washington (United States)

Topological insulation, a property initially observed in quantum systems, has recently been investigated in the context of mechanical meta-materials and phononic crystals. The design philosophy is to build an artificial structure, which forbids mechanical wave propagation in the bulk of structure, and allows unidirectional propagation along the surfaces/boundaries/edges. Though in one-dimensional settings, these edge waves are stationary, one can still observe the topological physics in action. A mechanical dimer system inspired by Su-Schrieffer-Heeger model, can be shown to make topological transition solely by changing the ratio of stiffness. However, practical systems offering in-situ control over such topological transitions are rare. The design and study of such systems not only can enable us to have easy control over their band-topology, but also can provide more insights into the topological dynamics at both theoretical and experimental levels.

In this study we present a one-dimensional mechanical dimer system, which shows topological band-transition by changing the initial static compressive force in the system. The system is made of discrete mass and spring elements. All masses are equal, but we use two types of springs (linear and non-linear) alternating along the chain. Strain-stiffening behavior of the non-linear conical spring allows us to change its instantaneous dynamic stiffness by changing the static compression in the chain. We can thus manipulate the stiffness ratio of the dimer system, and enforce topological transition of the band-gap just by statically compressing the chain. We numerically demonstrate and experimentally verify that this phenomenon is accompanied by the emergence of a distinct topologically protected edge mode inside the band-gap.

10170-114, Session PMon

Sound transmission loss of metamaterial thin plates with periodic subwavelength arrays of piezoelectric patches shunted with amplifier-resonator feedback circuits

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The sound transmission loss (STL) of metamaterial that consist of a homogenous plate and periodic subwavelength arrays of piezoelectric patches bonded to the surfaces of it is studied. The arrays of piezoelectric patches are shunted with amplifier-resonator feedback circuits in order to gain higher STL of the metamaterial plate. The numerical model based on the effective medium method are built and the explicit formulations is also developed for the calculation of STL of the metamaterial thin plates. Comparing with the metamaterial plate (proposed by Zhang et al.) that shunted by passive inductor-resistor resonant circuit, the metamaterial plate shunted by amplifier-resonator feedback circuits can achieve much higher STL within the mass-law region and the coincidence region of sound transmission. The STL peaks of the proposed metamaterial plate can be widened tremendously in the frequency ranges of 1000~3000Hz while the naissance of STL drop is avoided benefiting from the use of resistance in the circuits at the same time. By adjusting the parameters of the amplifier-resonator circuits, the bandwidth of the increased STL of the metamaterial plates can be significantly broadened in different frequency ranges. The influences of circuital parameters on STL and the equivalent Young's modulus as well as the equivalent dynamic bending stiffness are studied. Based on the explicit formulations of STL derived with the effective medium method, the mechanism of the unique STL of the metamaterial plates is also discussed.

10170-115, Session PMon

A novel nonlinear damage resonance intermodulation effect for structural health monitoring

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This manuscript is aimed at developing a theoretical model able to predict the generation of nonlinear elastic effects associated to the interaction of ultrasonic waves with the steady-state nonlinear response of local defect resonance (LDR). LDR is used in nonlinear elastic wave spectroscopy to enhance the excitation of the material damage at its local resonance, thus to dramatically increase the vibrational amplitude of material nonlinear phenomena. However, elastic wave spectroscopy experiments have shown that, using wide-band excitation, the nonlinear damage response of the medium is confined exclusively at the defect location.

The main result of this work was to overcome this limitation and prove both analytically and experimentally the generation of novel nonlinear elastic wave effects, here named as nonlinear damage resonance intermodulation, which correspond to a nonlinear intermodulation between the driving frequency and the LDR one. Beside these effects, also other nonlinear elastic wave phenomena such as higher harmonics of the input frequency and superharmonics of LDR frequency were found. The analytical model relies on solving the nonlinear equation of motion governing bending displacement for simply supported plates under the assumption of both

quadratic and cubic nonlinear defect approximation.

Transducer-based contact tests on a damaged composite laminate confirmed and validated these predictions and showed that using continuous periodic excitation, the nonlinear structural phenomena associated to LDR could be also featured at locations different from the damage resonance.

Because our findings can be applied to damaged metallic and composite materials, they will provide new opportunities for fully contact early detection and imaging of structural flaws.

10170-116, Session PMon

Numerical simulation on the temperature behavior of the main cable for suspension bridge

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The main cable is the key component of suspension bridges. Temperature variation of main cable causes the geometry changes of main cable, consequently, significantly affect the deflection of bridge deck and the stress state of the entire bridge, which may cause lot of trouble in bridge construction and operation maintenance. Therefore, it is very important to identify the real-time temperature of main cable in open environment. This paper investigates the temperature behavior of main cable of suspension bridges suing numerical simulation. Firstly, the basic theory and calculation methods for structural temperature analysis are briefly described and discussed. Secondly, a numerical analysis approach is proposed to calculate the temperature distribution and effect temperature of main cable taking account of the influences caused by surrounding climatic circumstances. Then, the finite element of a full scale main cable section is developed for numerical simulation. A comparison between the numerical studies and the experimental measurements is carried out to verify the feasibility and validation of the proposed method. This method can be applied in the design, construction and operational phases of the main cable for the temperature field calculation and prediction.

10170-117, Session PMon

Damage estimation of sewer pipe using subtitles of CCTV inspection video

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Recent frequent occurrence of urban sinkhole serves as a momentum of the periodic inspection of sewer pipelines. Sewer inspection using a CCTV device needs a lot of time and efforts. Many of previous studies which reduce the laborious tasks are mainly interested in the developments of image processing S/W and inspection H/W. And there has been no attempt to find meaningful information from the existing CCTV images stored by the sewer maintenance manager. This study adopts a cross-correlation based image processing method and extracts sewer inspection device's location data from CCTV images. As a result of the analysis of location-time relation, it show strong correlation between device stand time and the sewer damages. In case of using this method to investigate sewer inspection CCTV images, it will save the investigator's efforts and improve sewer maintenance efficiency and reliability.

10170-118, Session PMon

Structural health monitoring of fiber reinforced composites by means of CNTs

Flavia Libonati, Caudio Sbarufatti, Matteo Corbetta, Diego Scaccabarozzi, Simone Cinquemani, Politecnico di Milano (Italy); Alberto J. Suarez, Alejandro Urena, Univ. Rey Juan Carlos (Spain)

Composite materials, and in particular fiber-reinforced plastics (FRP), are widely used for structural applications, thanks to their favorable strength-to-weight and stiffness-to-weight ratios, and often preferred to conventional materials (e.g. steel) in some fields, such as aerospace, where low weight and high performance are strict requirements. The large use of fiber-reinforced composites for engineering applications makes it necessary to detect the presence of damage and to investigate its effect on their mechanical properties. To get information on damage and to understand how different types of damage can affect the mechanical performance of composites, a combination of different techniques is generally adopted. In particular, the combination of mechanical tests with nondestructive techniques (NDT) has become widely used for research purposes, allowing one to obtain more information regarding damage, from both mechanical and energetic viewpoints.

Structural health monitoring (SHM) is an essential part of composite design. Among different techniques, the most used ones are IR-thermography, ultrasounds, and acoustic emission. However, today SHM research strives to provide ongoing monitoring of a structure's integrity. Recent approaches include applying sensors to the surface of a structure or embedding sensors into a structure (e.g. optical fibers). These sensors can detect damage by reacting to changes in strain.

Here we aim to use CNTs, embedded into a composite material, as sensors for SHM, by taking advantage of their electrical conductivity. CNTs have already been adopted as strain sensors, by creating CNTs network into a material or by using CNT-coated fiberglass.

Here we probe the possibility of using CNTs as a reliable technique to be used for SHM of glass fiber reinforced (GFR) composite laminates. We carry out different types of mechanical tests (i.e. static, dynamic, and impact) on GFRP doped with CNTs. By performing resistance measurements, we aim to get important information on the material damage (e.g. damage onset and extent of damage). By carrying out different types of tests, we aim to correlate the damage type with the loading conditions, and we investigate the sensitivity of the CNT-sensors for different types of loads. Plates are manufactured using a limited amount of CNTs (0.1% wt.), appropriately chosen to endow the matrix with good electrical properties, without affecting mechanical performance of the whole composite material.

This technology has shown several advantages, providing cost effective solutions for SHM, which need to be scaled up to in situ monitoring of large components. Also, the unique properties of CNTs and their versatility make them applicable for a wide range of sensing tasks (e.g. strain, temperature, aging, and damage monitoring).

10170-119, Session PMon

A comparative study on book shelf steel structure based on frequency domain, time domain, and time-frequency plane modal analysis

Ardalan Sabamehr, Ashutosh Bagchi, Timir Baran Roy, Concordia Univ. (Canada)

Structural Health Monitoring (SHM) based on the vibration of structures has been very attractive topic for researchers in different fields such as: civil, aeronautical and mechanical engineering. The aim of this paper is to compare three most common modal identification techniques such as Frequency Domain Decomposition (FDD), Stochastic Subspace

Identification (SSI) and Continuous Wavelet Transform (CWT) to find modal properties (such as natural frequency, mode shape and damping ratio) of three story book shelf steel structure which was built in Concordia University Lab. The frame has made of Galvanized steel with 60 cm length, 27 cm width and 133 cm height with no brace along the long span and short space. Three 3-axial wireless accelerations (MicroStarin with 100mv/g accuracy) have been attached to the middle of each floor and gateway receive the data and send to the PC by use of Node Commander Software. The real-time monitoring has been performed for 20 second with 512 Hz sampling rate. The modified Complex Morlet wavelet have been selected for wavelet in order to use asymptotic signal rather than real one with variable bandwidth and wavelet central frequency. So, CWT is able to detect instantaneous modulus and phase by use of local maxima ridge detection. The result of all three methods have been compared and it demonstrated that CWT has the better performance in term of its accuracy in noisy environment with time-frequency appearance.

10170-120, Session PMon

Integration of fiber Bragg grating optic sensors for strain detection in prosthesis composed of CFRP composite

Jason Harris, California State Univ., Long Beach (United States)

The need for structural health monitoring, or the use of in-situ continuous measurement of structural operating parameters, was initially implemented in the fields of aerospace and civil engineering composites. Fiber optic sensors (FOS) are considered for these methods due to their high durability, negligible impact on embedded materials, insensitivity to electromagnetic fields, accuracy, and low cost. Our study focuses on the formation of artificial neural pathways for the use of structural health monitoring in prosthesis by means of Fiber Bragg Grating (FBG) optic sensors to detect shifts in strain. Implementation of these fibers are embedded into carbon fiber reinforced polymer (CFRP) based structures. CFRP was considered for its wide use application in ankle-foot prosthesis, which undergoes high loads of stress and wear. Carbon fiber based prosthesis of this type tend to have a larger tendency for increased wear and therefore require increased monitoring. This method of implementation of the FBG sensors act as a system of early detection which could prevent the prosthesis from critical failure due to previously undetected interior defects, further improving the patient's well being.

10170-121, Session PMon

Digitization of passive and active resonant shunting circuits and its application in smart piezoelectric metamaterial beams

Gang Wang, Xiaodong Zhang, Hunan Univ. (China)

Low cost digital controllers are designed in order to replace original analog electronic shunting circuits in the passive and active (the previously proposed amplifier-resonator feedback circuit) resonant piezoelectric shunting of smart metamaterial structures. By comparing with the formulations of analog circuits, the transfer functions of the digital controllers are deduced in order to fulfil the same effects of their analog counterparts. Then the Z-transform are conducted so that the transfer functions can be converted into programs of the digital controllers. As digital controllers can be readily adapted via wireless broadcasting, the bandgaps can be tuned easily instead of modifying the structure or the circuits of the metamaterial. Theoretical results are well verified experimentally with the measured vibration transmission properties where large insulations in low-frequency ranges are observed. Furthermore, a new method is developed to design the transfer functions of the digital piezoelectric shunting controllers directly and easily in order to gain multi locally resonant bandgaps with large attenuations on the proposed smart metamaterial beam. In the new design method, the poles and zeros of the transfer function related to the shunting units are adjusted directly, no matter if it can be realized through real analog circuits. The correlation between positions of zeros and poles in the transfer function and the attenuation peak, width and central frequency is also discussed.

10170-122, Session PMon

Performance assessment of engineering structures based on long-gauge FBG sensors: a review

Wan Hong, Nanjing Tech Univ. (China); Shizhi Chen, Southeast Univ. (China)

Long-gauge fiber Bragg grating (FBG) strain response is characterized by sensitivity to local damage and obtaining global behavior (e.g., deflection, natural frequency) of structures, and can be measured with high-accuracy and high sampling frequency. Recent research about performance assessment of engineering structures using long-gauge FBG sensors is reviewed in this paper. Firstly, description of long-gauge FBG sensing technique is presented. Secondly, assessment methods of structural local behavior using long-gauge strain response are classified into two types (time domain-based and frequency domain-based method). Time domain-based methods are those methods which directly use long-gauge strain to identify local damage of structures. Frequency domain-based methods are those methods which extract frequency features (e.g., modal macro-strain) of structures for damage identification. Thirdly, assessment methods of structural global behavior using long-gauge strain response are summarized. These methods include calculating deflection of structures from long-gauge strain response, extraction of natural frequency from dynamic strain time-history, and calculating displacement mode shape from modal macro-strain. Finally, suggestions on the selection of methods for performance assessment of engineering structures are proposed and some challenges are discussed.

10170-123, Session PMon

Modeling the strain monitoring data based on Copulas and its application in missing data recovery

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The dependence patterns of monitoring data among different strain gauges are complicated and diverse. How to characterize the complex dependence patterns and construct the joint distributions of strain data is an important topic in structural health monitoring. In recent years, Copulas are being increasingly used to flexibly model dependence structures and construct multivariate distributions of continuous random variables in many fields such as finance, actuarial sciences and hydrology, however, it has not been paid enough attention in structural health monitoring. In this article, Copulas are used to model the joint distribution of strain records in bridge structural health monitoring. The time series of strain records is decomposed into long-term trend, short-term trend, load-induced strain and noise. The long-term trend is described by regression and the noise is neglected in this study. Distributions of short-term trend and load-induced strain are modeled independently based on different Copulas. The bivariate Copula is used to model the joint distribution of two strain gauges' measurements, while Vine-Copula is used to model the joint distribution of multiple strain gauges' measurements. The joint distribution model has been successfully applied in the missing data recovery problem. The missing data is recovered by three-step recovery process. Firstly, the missing marginal distribution of the faulty sensor is estimated by combining the information of its historical

measurements and other normal sensors' current measurements, then the missing time series (short-term trend and load-induced strain) of a faulty sensor is reconstructed by sequentially sampling from the distribution model conditional on the nearby normal sensor's time series, and the long-term trend is finally estimated based on the regression model. The study shows this approach is able to recover long-period missing strain measurements such as the whole day lost problem.

10170-124, Session PMon

Automated vehicle counting using image processing and machine learning

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Abstract: Vehicle counting can be used by the government to improve roadways and flow of traffic, and by private businesses to determine the value of locating a new store in an area. A vehicle count can be performed manually or automatically. Manual counting requires an individual to go to the site of the count and tally the cars going by electronically or by hand. Automatic vehicle counting can be done by placing a camera at the count site and having an individual count the cars on the tape at a later date. Another version of automatic counting can be done via pneumatic tube which is set up across the road and as a car drives across the tube an air pressure change is detected and marked. This paper presents a low cost method to perform automatic vehicle counting. The method utilizes a Raspberry Pi micro-computer to record videos, uses image processing to detect when a car is in a lane, and outputs an accurate count of vehicle movements. The Raspberry Pi records the video in real time and runs the video frame by frame against a database of images with cars in them and, with the use of machine learning, is able to tell when the current image contains a car. This method avoids fatigue issues that are encountered in manual and automatic video counting. It also prevents the disruption of roadways that occurs when installing pneumatic tubes.

10170-125, Session PMon

Using LabView for real-time simulation of monitoring and tracking process a plurality of biological objects

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Currently, relevant and wide researched is the tasks of studying and tracking in real time the dynamics of various biological objects. Specificity of specific objects, conditions for their visualization and model parameters strongly influence the choice of methods and algorithms optimal for a specific task. Therefore, in this article, in order to automate the processes of adaptation algorithms of recognition - tracking, we suggest going to discuss several projects trackers in Labview. They allow you to change templates, educate, adapt the number of frames in their subtraction, to the speed of the objects and statistics of noisy images. The new compared functions of patches and / or their features and descriptors , methods of preprocessing, that improve tracking multiple objects, will be discussed. There will also be analyzed experiments conducted to verify the work of trackers on the actual video files.

10170-126, Session PMon

Ultrasonic wave mixing for nonlinear ultrasonics in viscoelastic finite volume fluids

Andriejus Demcenko, Rab Wilson, Julien Reboud, Jonathan M. Cooper, Univ. of Glasgow (United Kingdom)

Nonlinear interactions between two initial ultrasonic waves can result in nonlinear waves of combined (sum and difference) frequencies in fluids. The main advantage of wave mixing for nonlinear ultrasonics is the possibility to select the initial waves in such a way that the nonlinear signals of the combined frequencies are separated from unwanted harmonics, which can be generated uncontrolledly by electronics or surrounding media.

We show experimentally that a strong nonlinear interaction occurs in finite volume fluids (microliter droplet), using guided ultrasonic waves propagated on 128° Y cut LiNbO3, by two interdigitated transducers at 1.893 and 3.445 MHz frequencies. The nonlinear waves at the combined frequencies are detected using both laser vibrometry and a hydrophone, in a range of organic and inorganic fluids of different viscosities, providing a route towards the visco-elastic characterization of fluids. The initial experiments show that ultrasonic wave mixing is an attractive technique for the nonlinear ultrasonic characterization of the finite volume fluids, when there is limited availability of the sample materials.

10170-127, Session PMon

Advances in acoustic source localization in an anisotropic plate without knowing its material properties

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Acoustic source localization (ASL) in a highly anisotropic plate is a challenging task. The basic assumption in many of the currently available techniques is that the wave propagates along a straight line from the source to the receiving sensor. However, waves in anisotropic solids propagate along curved lines and form non-circular wave fronts. As a result, for a highly anisotropic solid the acoustic source localization techniques that assume straight line propagation of waves from the source to the receiver are bound to produce a significant error.

In this paper a new technique is introduced for acoustic source localization in an anisotropic plate by dealing with non-circular shape of wave fronts. Direction vectors of the wave fronts are computed from the Time-Difference-Of-Arrivals (TDOA) at three sensors placed in a cluster, then they are cast into a geometric vector analysis or an optimization process to accurately obtain the acoustic source location. Two common wave front shapes in highly anisotropic plates, rhombus and ellipse, are analyzed. Following this analysis, the acoustic source could be successfully localized without knowing the material properties of the plate. The proposed technique is experimentally verified.

10170-17, Session 7

Adaptive on-line signal denoising using stochastic resonance for acoustic emission-based structural health monitoring

Jinki Kim, Univ. of Michigan (United States); Ryan L. Harne, The Ohio State Univ. (United States); Kon-Well Wang, Univ. of Michigan (United States)

Noise is unavoidable and ever-present in measurements. As a result, signal denoising is a necessity for many scientific and engineering disciplines. In particular, structural health monitoring applications aim to detect weak anomaly responses generated by incipient damages from background noise that contaminates the signals. Among various approaches, stochastic resonance has been widely studied and adopted for denoising and weak signal detection to enhance the reliability of structural heath monitoring applications. On the other hand, many of the advancements have been focused on detecting useful information from the frequency domain generally in a post-processing environment, such as identifying damage-induced frequency changes that become more prominent by utilizing stochastic resonance in bistable systems, rather than recovering the original time domain responses. In this study, a new adaptive signal conditioning strategy is presented for on-line signal denoising and recovery. The core of the new approach is utilizing the stochastic resonance in a bistable dynamic system to average out the noise-induced stochastic transitions. The input amplitude to the bistable system is adaptively adjusted to favorably activate the stochastic resonance based on the noise level of the given signal, which is one of the few quantities that can be assessed from noise contaminated signals in practical situations. Numerical investigations demonstrate the operational principle and confirm the denoising performance of the new method. Experimental verification with denoising and recovering acoustic emission signals by employing a double-well Duffing analog circuit exemplifies the promising potential of implementing the new denoising strategy for enhancing on-line acoustic emission-based structural health monitoring.

10170-35, Session 7

Development and testing of a multi-transducers system for the measurement of the height of condensed water in steam pipes with steady-state and turbulence flow conditions

Shyh-Shiuh Lih, Hyeong Jae Lee, Yoseph Bar-Cohen, Mircea Badescu, William Cervantes, Jet Propulsion Lab. (United States)

One of the critical requirements of ensuring the safety of a steam pipe is to monitor the condensed water level under operation. For this objective, the authors initially developed methods and obtained preliminary test results based on the use of ultrasonic pulse-echo transducers and enhanced signal processing method, which they reported in previous publications. The methodology needed further development to perform measurements in more disturbing dynamic flow conditions. To verify and obtain maximum benefit from those developed technologies, an experimental model testing system was developed using multiple transducers driven by a multiplexer, and data acquisition module that is operated at steady-state and turbulence flow conditions. The model testing results allow to simulate prototype performance over a range of flow rates and water levels and to observe flow conditions and patterns, as well as measure actual water level, flow velocities, wave conditions, etc. In this paper, we will present the development details that include description of the testbed for simulating the flow of condensed water, the multiple transducers arrangement, the graphical user interface of the signal processing method, and test results. By using the developed test system and through a series of systematic parametric model testing, it was demonstrated that the developed water height measurement system with the multi-transducers system and signal processing method is an efficient, accurate, and versatile tool. This paper will also discuss the possibility of using the developed system to monitor water levels and flow speed to prevent critical operation conditions such as cavitation and water-hammering.

10170-36, Session 7

NIR intensity sensor for water pressure monitoring

Wei-Chih Wang, Univ. of Washington (United States) and National Tsing Hua Univ. (Taiwan)

Secondary cooling presents control challenges. Conventional feedback control systems cannot be used effectively due to the insufficient reliability of temperature sensors. Here we propose a simple optical technique in placing intensity based portable optical sensor for a rapid nondestructive calibration of water distribution and pressure on dummy bar from nozzles in the secondary cooling system. For non-destructive testing, the proposed system would make use of the data collected by the optical sensor array to help calibrate the water nozzles in temperature control in cooling system. In this paper, we will present the design and characterization a new optical water pressure sensor. Initial field test shows this NIR intensity sensor is capable of operating in the specified range with good repeatability and low hysteresis.

10170-37, Session 7

Diffuse field reconstruction for near surface imaging

Anthony J. Croxford, Jack Potter, Univ. of Bristol (United Kingdom)

Ultrasonic phased arrays offer excellent performance for detecting and classifying defects, however when inspecting near the array there is typically a deadzone where electrical cross talk saturates the response making it impossible to measure. In many situations this can be mitigated through the use of a physical standoff, however for permanently installed systems or in situ inspection of components in access restricted areas such as gas turbines such a solution is impossible. This paper reports on an approach that allows ultrasonic measurements to be made of the near surface region.

Specifically by measuring the diffuse response of the system it is possible to reconstruct the greens function between any pair of transducers. As this is created from data that is not saturated there is no deadzone in the resulting image. When combined with advanced sampling techniques using hadamard coding the region immediately in front of the array can be imaged with performance similar to that seen in the bulk material despite this reconstruction approach.

In this paper the fundamental of the reconstruction and sampling technique are explained and demonstrated with images shown for defects within 0.5mm of the sample surface in both aluminium and composite components.

10170-38, Session 7

Development of BS-PT based high temperature ultrasonic transducer

Prathamesh Bilgunde, Leonard J. Bond, Ctr. for Nondestructive Evaluation, Iowa State Univ. of Science and Technology (United States)

Liquid metal cooled reactors, using sodium or lead-bismuth, operate typically at 250C in hot stand-by mode. Such a high temperature environment poses a major challenge in terms of development of ultrasonic transducer which is a key enabling technology for structural health monitoring of reactors. The transduction ability of the transducer mainly depends upon (i) Piezoelectric material (ii) backing element (iii) matching layer and (iv)interfacial bonding agent.

In the current work, BS-PT [(1-x) $BiScO_3$-$xPbTiO_3$] piezoelectric material based ultrasonic transducer is proposed for such high temperature (HT)

applications. A finite element model has been developed based on theory of linear piezoelectric effect. Using the temperature dependent experimental data, the transient study estimates only 2dB transduction loss due to BSPT when the temperature is increased from 15C to 300C.The simulated amplitude of the wave transmitted shows negligible loss till 200C indicating temperature stability of BS-PT compared to PZT-5A. This proposed model allows rapid evaluation of a piezoelectric material for HT applications. The numerical data is compared with experimental data for pulse-echo contact measurements.

A backing element is developed based on HT epoxy and tungsten particles to provide optimal acoustic impedance and attenuation. Acoustic coupling of piezoelectric element to the backing and matching layer is investigated using commercially available high temperature adhesives. HT pulse-echo contact measurements are performed using SS304 and SS316 specimens. Ultrasonic immersion measurements are performed in silicone oil bath till 200C. Signal to noise ratio of the transducer as a function of temperature is reported for contact and immersion measurements.

10170-39, Session 7

Adaptation of electromechanical impedance SHM for space-based platforms

David C. Hunter, Andrei N. Zagrai, New Mexico Institute of Mining and Technology (United States); Seth S. Kessler, Metis Design Corp. (United States)

Ultrasonic structural health monitoring (SHM) is used to detect damage in structures ranging from pressure vessels and pipelines to aircraft and wind turbines. Until recently, applications to space systems have been rare, mostly focusing on pre-launch diagnostics. Implementation of ultrasonic SHM normally involve an array of piezoelectric wafer active sensors connected to digital data acquisition system which, depending on the selected approach, collect ultrasonic pulse, continuous wave (CW), or modulated signals. In this contribution, adaptation of electro-mechanical impedance SHM for space-based platforms is explored. Typical hardware configurations for miniaturization of impedance measurements are reviewed and theoretical descriptions are considered. Previous studies have demonstrated utility of electromechanical impedance measurements in assessing integrity of certain components of space systems and sensor self-diagnosis. The paper describes a path for implementing electro-mechanical impedance measurements into a miniaturized commercial system, aiming at expanding modality of measurements and damage detection capabilities.

10170-40, Session 8A

A numerical and experimental study on the performance of acoustic black hole based metamaterials

Hongfei Zhu, Univ. of Notre Dame (United States); Fabio Semperlotti, Purdue Univ. (United States)

Multi-material based metamaterials provide several opportunities to manipulate and tailor the propagation of acoustic waves. However, the fabrication complexity and lack of structural performance has prevented their application to the design of structural systems. Acoustic Black Holes (ABH) based metamaterials were recently introduced in order to bridge this gap and provide two-dimensional materials having ease of fabrication and load-bearing capabilities without compromising on high-level dispersion and propagation performance. In this study, we present a numerical and experimental investigation of ABH 2D acoustic metamaterials with particular attention to the performance in both the long and short wavelength limits. ABH materials offer an excellent opportunity to design acoustic lenses that are fully embedded into the host structure. The design strategy and the performance of these lenses are discussed in details, supported by numerical and experimental results.

10170-41, Session 8A

A mechanical power dissipation model for axially loaded metamaterial bars

Hasan Al Babaa, Mostafa A. Nouh, Univ. at Buffalo (United States)

Elastic metamaterials are sub-wavelength structures with locally resonant components that contribute to the rise of tunable stop bands, i.e. frequency ranges within which waves don't propagate. A new approach is presented here to quantify this stop band behavior by evaluating structural vibrating power flowing in the different constituents of locally resonant metamaterials. It is shown that the patterns of power propagation match steady-state wave profiles derived from displacement fields, and can thus be used to develop an algorithm that numerically predict stop band frequencies for any given realization with a finite length and a known number of repeating cells.

10170-42, Session 8A

Mechanical metamaterials: recent advances and opportunities in structural health monitoring

Eduard Karpov, Larry Danso, Univ. of Illinois at Chicago (United States)

Mechanical metamaterials and metastructures show responses to static loads that can be interpreted as a negative elastic modulus or a negative Poisson ratio by a combination of simple mechanical elements, bars and springs. One recent study [1-2], also uses a structural bistability at the unit cell level to deploy a load-induced polymorphic phase transformation in the entire sample. When properly designed, this phase transformation can lead to a contraction of the sample in the direction of an increasing load, a manifest of the negative extensibility phenomenon. In this presentation, we overview recent developments in mathematical analysis of mechanical metamaterials, discuss the paths toward design and fabrication of these interesting materials, and outline their opportunities for structural health monitoring and intelligent structures applications. [1] Nicolaou ZG, Motter AE. Nature Materials 11, 608, 2012. [2] Chen ML, Karpov EG. Physical Review E 90, 033201, 2014.

10170-43, Session 8A

Nonlinear dynamics of a lattice of bi-stable units with defects

Myungwon Hwang, Andres F. Arrieta, Purdue Univ. (United States)

The utilisation of nonlinearity for creating novel dynamical behaviour in periodic lattices has attracted significant attention owing to the great potential for generating wave guiding [1, 2], tuning band gaps [3, 4], acoustic rectification [5] and energy harvesting [6, 7]. Most studies on nonlinear lattices have been presented in the context of granular media [8], with the inter-element (inter-site) force typically providing the source of nonlinearity. Experimental realisations of lattice systems with nonlinear on-site potential forces have been thus far less explored, despite the theoretically demonstrated substantial potential for generating extreme dynamics with broad applications [9, 10, 11, 12]. Recently, experimental studies on system featuring bi-stable on-site potentials (described by phi 4 models) demonstrate strongly directional wave propagation and robust signal transmission in such lattices [13, 14]. Nevertheless, the dynamic behaviour and its potential for engineering applications remain to be fully explored.

This paper focuses on the experimental investigation of the nonlinear wave propagation of a lattice system subject to a nonlinear on-site potential produced by bi-stable unit cells including engineered defects. The conditions for which the propagating wave can overcome the defect presence are experimentally investigated by varying the parameters of the lattice. The investigation of the ratio of energy lost to localised vibrations on the defect is estimated utilizing numerical and experimental methods. This study will provide experimental indications of the breaking of periodicity in lattices of bi-stable structures, a subject that has rarely been previously investigated.

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10170-44, Session 8B

Ultrasonic damage imaging of structural components with bulk and guided waves using match coefficients

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Damage imaging of structural components in the field of Non Destructive Evaluations (NDE) and Structural Health Monitoring (SHM) using ultrasonic waves is usually performed by conventional imaging techniques, such as Delay-And-Sum (DAS), by back-propagating the recorded waveforms to identify locations and size of defects and damages. This technique results in sidelobes and artifacts that worsen the accuracy of the damage identification. Here we propose a novel imaging approach that derives from the well-known technique of Matched Field Processing (MFP), often used in underwater acoustics and seismology. In MFP, the source or damage is located by a matching procedure between measurements (“data vector”) and expected responses (“replica vectors”) computed for each point of the imaging volume. In this work, we apply this matching approach only to selected features extracted from the recorded waveforms. These features, for example time-of-flights or amplitudes, will be selected for multiple modes of propagation of the ultrasonic waves (longitudinal and shear in bulk waves, multiple guided modes in waveguides). By considering multiple features and multiple wave modes, it is possible to increase the performance of this matching procedure, which can be possibly further improved by also combining different signal frequencies and excitation sources in analogy with biomedical ultrasonic imaging. Different correlation metrics will be tested as matching coefficients in order to identify the ones that show higher sensitivity to damages and defects. These metrics, along with the whole algorithm, show a high computational efficiency in the image reconstruction process. Applications of this imaging approach will be shown for bulk solids and plate-like structures.

10170-45, Session 8B

Nondestructive assessment of waveguides using an integrated electromechnical impedance and ultrasonic waves approach

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In this paper, we present a structural health monitoring (SHM) paradigm based on the simultaneous use of ultrasounds and electromechanical impedance (EMI) to monitor waveguides. The paradigm uses guided ultrasonic waves (GUWs) in pulse-echo and pitch-catch mode and EMI simultaneously. The three methodologies are driven by the same sensing/hardware/software unit. To assess the feasibility of this unified system an aluminum plate was monitored and its repeatability under varying environmental conditions was evaluated. Damage was simulated by adding small masses to the plate. The results associated with pulse-echo and pitch-catch GUW testing and with EMI monitoring show that the proposed system is robust and can be developed further to address the challenges associated with the SHM of complex structures.

10170-46, Session 8B

Guided wave attenuation in composite materials

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In this paper problem of guided wave attenuation in composite materials is investigated. In this purpose numerical model based on Spectral Element Method (SEM) is utilized. Numerical model includes also the piezoelectric transducer and bond layer between actuator and the host structure. In this paper two methods of a composite laminate modeling are proposed. First method is based on homogenization of material properties in one layer of 3D brick spectral elements. The second method is based on approach where each ply is simulated by separate layer consisting of 3D brick spectral elements. Moreover, results of comparison of both presented modeling methods are discussed. Numerical results are experimentally validated using Scanning Laser Doppler Vibrometry (SLDV) measurements. Guided waves are excited using piezoelectric transducer and registered using non-contact device – the laser vibrometer. Validation is based on signals gathered in single dispersed points as well as on full wavefield measurements. The full wavefield measurements are based on dense grid of points. In this paper results for simple uniform composite laminate as well as more complex structural composites in the form of honeycomb plate and panel with stiffeners are presented. Paper presents result for composite structures in pristine state (reference) and for damaged cases. Investigated damage is in the form of delamination.

10170-47, Session 8B

Guided waves based SHM systems: parameters selection for better identification and localization of damages in composites stiffened plates

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Structural Health Monitoring deals mainly with structures instrumented by secondary bonded or embedded sensors that, acting as both signal generators and receivers, are able to "interrogate" the structure about its "health status". This innovative approach to the damage analysis is particularly promising for reducing the maintenance costs and eventually the weight of aerospace composite structures, without any reduction of the safety level required. These structures are currently designed and employed with significant reduction of the pristine material allowables to take in account of certain failure mechanisms that frequently bring to relatively small hidden damages called Barely Visible Damages, consisting among others in delaminations and/or debondings and being detectable only by specific instruments operated by trained personnel. It has been proved that the propagation of guided waves is affected by the presence of such type of damages, but their effective identification and localization depends on the accurate "tuning" of the wave characteristic (frequency, amplitude, velocity, mode) as well as on the proper selection of the best parameter of the specific wave mode selected and data analysis algorithm.. The intent of this paper is to summarize the experiences gained by the authors in selecting the most sensitive parameters according to the type of damage to be investigated in several typology composite plate-like structures.

10170-48, Session 9A

An analytical model for band gap behavior in lumped elastic metamaterials

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Internal resonators in lumped spring-mass elastic metamaterials reveal unique wave dispersion characteristics. Using the Bloch-wave analysis and the Transfer Matrix Method (TMM), the band structure of the unit self-repeating cell shows two dispersion branches and a band gap region at the vicinity of the natural frequency of the internal system. Despite the lack of a damping component, the frequency response of finite elastic metamaterials shows a significant drop in magnitude at band gap frequencies. An analytical model of the structural dynamics of a series of metamaterial cells is presented here to quantify and help understand this behavior.

10170-49, Session 9A

Wave localization in beams due to band inversion

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We use a simple one-dimensional phononic crystal (PC) comprised of a beam with periodically alternating cross-sections to demonstrate the phenomenon of frequency band inversion for both quasi-longitudinal and bending modes. By varying the geometric properties of the unit cell, a topological transition point is observed where the second bandgap of the PC closes. Before and after this transition point, the bandgap reopens and exhibits an inversion of eigenfrequencies corresponding to modes with different symmetry. A finite system then is considered formed by two PCs with different topological parameters connecting to each other and they are chosen from each side of the transition point with similar second bandgap feature. For both quasi-longitudinal and bending modes, a surface mode is identified at the interface between the two PCs within the frequency range of the bandgap, which results in a strong localization of energy.

10170-50, Session 9A

Nonlinear wave dynamics of hollow ellipsoidal cylinder lattice

Hyunryung Kim, Francesca C. Green, Univ. of Washington (United States); Eunho Kim, Chonbuk National Univ. (Korea, Republic of); Jinkyu Yang, Univ. of Washington (United States)

In this presentation, we describe how stress waves propagate in hollow cylindrical lattices, where geometric nonlinearity is involved. Hollow cylinders have a decreasing Poisson's ratio as they are compressed in a large scale. We focus on the contact mechanics affecting the wave dynamics in hollow cylinder arrays. A finite element method is used to conduct numerical analysis both in static and dynamic cases. First, in the static setting, we investigate the force-displacement relationship between two hollow ellipsoidal cylinders (HECs), when they are under uni-axial compression applied along the major and the minor axis. We find that the HECs show a strain-hardening dominant behavior along the minor axis. Along the major axis, however, HECs experience a transition from strain-softening to hardening under large deformation. Next, we investigate the dynamic behavior of the HEC lattice structures by giving a high impact along the major direction. For this, we use a block striker hitting on the top center of the array, inducing a strong geometric nonlinearity in the system. Parametric study shows that the higher the striker mass is, the slower the wave propagates along the impact direction. This results in a lower tangent of the wave propagation direction. The same is observed with increasing striker velocities. This is due to the fact that waves with higher amplitude travel slower in strain-softening systems and faster in strain-hardening systems. The findings from this study can help us better understand how stress waves propagate in periodic nonlinear media. This will, in turn, contribute to the design and development of wave tailoring devices for energy harvesting and impact mitigation.

10170-51, Session 9A

Acoustic vortex beam generation using a compact metamaterial aperture

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The total angular momentum of a system can be divided into spin angular momentum and orbital angular momentum (OAM). Both electromagnetic and acoustic OAM waves have recently gained a lot of attention due to their extremely diverse range of applications, including enhanced phase contrast imaging, super-resolution acoustic sources, and micro-particle manipulation. The wavefront of an OAM wave has a corkscrew shape, and can be defined by a topological mode number L which dictates both the chirality of the wavefronts (mode sign) and number of wavefronts (mode magnitude).

Inspired by recent research on acoustic leaky-wave antennas (LWA), we present an novel air-acoustic vortex beam emitter capable of generating topologically diverse wavefronts, including both integer, and fractional vortex waves. An acoustic LWA is a device composed of a one-, or two-dimensional waveguide which leaks power along its length with either a uniform, or periodic leakage aperture. By wrapping a one-dimensional, linear LWA back upon itself, the planar wavefront is wrapped to a helical phase front, or vortex wave. By sweeping through the input frequency in the waveguide, the topological mode of the radiated vortex wave can be continuously tuned. We have designed a vortex wave antenna which is capable of generating at least 7 distinct topological modes. The chosen sub-wavelength geometry was modeled using a finite element multiphysics model to predict the radiated wavefields of the antenna as a function of frequency. It was then built using additive manufacturing techniques and tested in air, demonstrating continuous mode variation of propagating vortex waves.

10170-52, Session 9A

Analyzing the frequency band gap in functionally graded materials with harmonically varying material properties

Mohammad Hossein Ansari, M. Amin Karami, Univ. at Buffalo (United States)

The design and modeling of a bar made of functionally graded materials are studied in this paper. The material properties of the bar harmonically vary along the bar. The bar is mathematically modeled and its governing equation is derived. The mode shapes and the natural frequencies of the system are calculated analytically using the boundary conditions at the two ends of the bar. The wave propagation in the bar is studied and the frequency band gaps of the system are calculated. It is shown that by varying the material properties of the bar, we can design a system with a desired frequency band gap. Such a system can be used for vibration damping and sound isolation. This new class of meta-materials are generalization of periodic structures. In periodic structures a feature repeats periodically so the meta-material is spatially periodic. The new class of meta-materials proposed in this paper is not only periodic but is also harmonic. This allows treatment of the system using analytical modal analysis, and calculation of the modal properties using integration. This functionally graded material can be realized through utilization of smart materials, and specifically magneto rheological fluids.

10170-53, Session 9A

Scattering of longitudinal acoustic phonons in thin silicon membranes

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Phononic cystals (PnCs) are the acoustic equivalent of photonic crystals, where a periodic array of scattering inclusions in a homogenous material forbids certain ranges of acoustic frequencies from existence. The past decade[1-3] has seen a rapid growth in the study of these PnCs. Most of the studies have focused on the existence and properties of phononic band gaps. However, relatively little attention has been paid to investigating how surface roughness affects the phonon propagation through such materials. This work focuses on understanding how surface roughness influence phonon transport through acoustic measurements in nanostructures with well-characterized surface morphologies. We employ a femtosecond laser pump-probe setup to excite and measure the lifetimes of sub-THz longitudinal acoustic phonons in ultrathin silicon membranes down to 36 nm. We show that the phonon lifetime for membranes thicker than 200 nm is limited intrinsically by Akheiser mechanism. However, for thinner membranes, boundary scattering is the most dominant dissipation mechanism. Perturbation-based spectral scattering theory does not seem to reproduce the observed trend in phonon lifetimes. We use a surface specularity parameter based on Kirchhoff's approximation to correctly predict the observed trend. Our results provide insights to understanding thermal and acoustic transport in nanostructures.

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10170-54, Session 9A

Smart Kirigami open honeycombs in shape changing actuation and dynamics

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Kirigami is the ancient Japanese art of cutting and folding paper, widespread in Asia since the 17th century. Kirigami offers a broader set of geometries and topologies than classical fold/valleys Origami, because of the presence of cuts. Moreover, Kirigami can be readily applied to a large set of composite and smart 2D materials, and can be used to up-scaled productions with modular moulding. We describe the manufacturing and testing of a topology of Kirigami cellular structures defined as Open Honeycombs. Open Honeycombs (OHs) can assume fully closed shape and be alike classical hexagonal centresymmetric honeycombs, or can vary their morphology by tuning the opening angle and rotational stiffness of the folds. We show the performance of experimental PEEK OHs with cable actuation and morphing shape characteristics, and the analogous morphing behaviour of styrene SMPs under combined mechanical and thermal loading. We also show the dynamic (modal analysis) behaviour of OHs configurations parametrised against their geometry characteristics, and the controllable modal density characteristics that one could obtain by tuning the topology and folding properties.

10170-55, Session 9A

Gradient-index based smart metacomposite for elastic wave focusing

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We designed and analyzed a piezo-lens to focus flexural waves in thin plates. The piezo-lens comprises a host plate and piezoelectric patches bonded on the surfaces of the plate. The piezoelectric patches are shunted with negative capacitance circuits. The effective refractive indexes inside the piezo-lens are designed to fit a hyperbolic secant distribution by tuning the negative capacitance values. A homogenized model of piezo-mechanical system is adopted in the designing process of the piezo-lens. The wave focusing effect is studied by the finite element method. Numerical results show that the piezo-lens can focus flexural waves by bending their trajectories, and is effective in a large frequency band. The piezo-lens has the ability to focus flexural waves at different locations by tuning the shunting negative capacitance values. Potential applications of the piezo-lens include energy harvesting, SHM, etc.

10170-56, Session 9B

Directionality of A0 lamb wave mode scattering at defects

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Localized and distributed guided ultrasonic waves array systems offer an efficient way for the structural health monitoring for large structures. The detection sensitivity for fatigue cracks depends on the orientation of the crack relative to the location of the sensor elements. Crack-like defects have a directionality pattern of the scattered field depending on the angle of the incident wave relative to the defect orientation and on the ratio of the defect depth and length to the wavelength. From FE simulations it has been shown that for cracks and notches almost no energy is scattered in certain directions from the defect, i.e., the data processing algorithm must take into account that for some transducer combinations no change in the signal even for a significant defect will be detected. The scattered wave field directionality pattern for an incident low frequency A0 Lamb wave mode was predicted from 3D Finite Element simulations and verified from experimental measurements at machined part-through and through-thickness notches using a laser interferometer. Good agreement was found and the directionality pattern can be predicted accurately. The amplitude of the scattered wave is quantified for a systematic variation of the angle of the incident wave relative to the defect orientation, the defect depth, and the ratio of the characteristic defect size to the wavelength. Based on these results the detection sensitivity for crack-like defects in plate structures using guided wave sensors arrays can be quantified.

10170-57, Session 9B

Guided waves scattering by a geometrical or damage feature: application to fatigue crack and machined notch

Nicolas Quaegebeur, Nidhal Bouslama, Maxime Bilodeau, Patrice Masson, Ahmed Maslouhi, Philippe Micheau, Univ. de Sherbrooke (Canada)

Validation of guided-wave based systems for Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM) under realistic conditions or environment requires complex setups. For this purpose, numerical or theoretical approaches are useful to save time and cost associated with experiential tests. However, the interaction with realistic geometrical (rivets, thickness changes, stiffeners, extrusions) or damage features (fatigue cracks, fillet cracks, delaminations, disbonds) must be accurately captured in order to be representative. In this paper, an experimental methodology is presented for estimating the far-field scattering of geometrical or damage features. The principle is based on the use of a Hankel transform of the measured 3D velocity field in order to evaluate with precision and repeatability the scattered pattern using a spatially averaged method. Application to scattering of a hole with simulated machined and real fatigue cracks is proposed. It is observed that the simulated machined crack generally used as a reference standard can only model accurately the transmission behaviour while the scattering patterns are only similar when the wavelength is about the size of the crack, limiting the practical use of machined cracks for experimental validation of SHM or NDE systems.

10170-58, Session 9B

Beamforming of Lamb waves using 2D array based on Fermat spiral

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2D arrays that enable unequivocal damage localization have shown a great application potential for structural health monitoring (SHM) of plate-like structures. Performance of such arrays depends on numerous factors, e.g. number of elements, inter-element distance, apodization, etc. Optimization of the arrays' topology, aiming at obtaining the best image quality using the lowest number of elements, has been investigated over the last years. Numerous shapes, e.g. circular, square or star-like arrays, have been presented in literature.

Here, we present an array topology designed for bemforming of Lamb waves based on Fermat's spiral, which results in a sunflower-like elements distribution. Due to the variable element pitch (thinning) this concept allows for obtaining array characteristics superior to conventional uniformly distributed topologies. In the paper the array performance is discussed in terms of main-lobe width and side-lobes level. The beampattern parameters are investigated for a 360 degrees azimuth of interest. In the first step, the array pattern is evaluated analytically, and then its performance is verified by means of both numerical simulations of wave propagation and experimentally, using laser Doppler vibrometer.

10170-59, Session 9B

Lamb wave interaction at debondings due to impact damage in complex stiffened CFRP structures

Benjamin Eckstein, Airbus Group Innovations (Germany); Maria Moix Bonet, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Martin Bach, Nicolas Dobmann, Airbus Group Innovations (Germany)

The increasing usage of Carbon Fiber Reinforced Plastics (CFRP) for primary aerospace structures involves dealing with the principal susceptibility of composite laminates to impact loads as well as the occurrence of barely visible impact damages. One special case among the variety of impact sources is the so called blunt impact, which may cause primarily damage to the internal structure.

Thus, the assessment of debonding of stiffening elements in CFRP structures poses an attractive application case for Structural Health Monitoring by Guided Ultrasonic Waves. Wave propagation phenomena at impact damages as well as the utilized signal processing to extract a damage related feature (i.e. damage index) contribute to the sensitivity and thus to the reliability of SHM systems.

This work is based on data from the EU-funded project SARISTU, where a generic CFRP door surrounding fuselage panel with an integrated sensor network has been built and tested by introducing a large number of impact damages.

Wave interaction of stringer debondings of different size and morphology in omega-stringer stiffened structures are examined to highlight the factors contributing to the sensitivity. In order to support this analysis, wave field data measured by air-coupled ultrasound is used in addition. Common damage indicator formulations for use with imaging algorithms, such as the Reconstruction Algorithm for the Probabilistic Inspection of Damage (RAPID), are applied on data from various damage cases. Furthermore, the difference in detectability of debondings and delaminations as well as the implications on imaging algorithms are examined.

10170-60, Session 9B

Damage feature extraction from Lamb wave signals of a door surround structure

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The activities around an aircraft Door Surround Structure (DSS) during in-service can lead to Barely Visible Impact Damages (BVID) in the composite structure. The potential presence of BVID in a structure implies increased maintenance efforts to ensure the structure performance. Structural Health Monitoring (SHM) aims to be used as a complement of traditional non-destructive inspection, enabling a decrease in maintenance efforts.

This work focuses on the detection of damages that occur after impacting a composite aircraft DSS by means of Acousto Ultrasonics. A composite DSS with an integrated SHM network is manufactured within the EU-funded SARISTU project. The structure is afterwards impacted, inducing skin delaminations and debondings of stringers, frames and clips. The experimental Lamb wave signal acquired throughout the impacting campaign allows the subsequent damage assessment.

Multiple mode propagation, mode conversion or wave reflections make the analysis of Lamb waves rather complex. Hence, the signal interpretation is an essential step for the damage assessment. This paper explores the detection of realistic damages in a composite DSS using sparse signal reconstruction methods on the Lamb signal and afterwards extracting damage sensitive features.

Advantages of working with extracted features are the decrease in data volume, the increase in signal comprehension and the simplification of the signal compensation for variable environmental and operational conditions. Challenges regarding the detection with a sparse reconstructed signal are the correct separation of overlapping features and the extraction of the damage relevant parameters.

10170-61, Session 9B

Laser Doppler vibrometry and PZT sensing for the study of guided waves in a stepped aluminum plate

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Lamb waves propagating in thin plates and shells are being studied widely for their potential applications in nondestructive inspection of large-scale structures. These structures are generally characterized by the presence of geometrical discontinuities such as stiffeners, mechanical joints or variable thicknesses that affect the propagation characteristics of Lamb waves and that can be very similar to those from defects occurring in service (delamination, disbond, etc.). Therefore the knowledge of the effects of such discontinuities on the propagation of Lamb waves is essential to avoid their false identification as defects. In this work Lamb waves propagating in a metal plate with a step discontinuity in its thickness are studied through laboratory experiments and numerical simulations. A single 10 mm piezoceramic disk (PZT) bonded to the host structure using cyanoacrylate gage adhesive is utilized for Lamb waves generation and the responses are measured at multiple locations, along a line, before and after the step, using a scanning Laser Doppler Vibrometer (LDV, Polytec PSV-400). The use of a non-contact sensor is essential in this work, due to the local effects of the discontinuities, requiring a dense number of acquisition points. To increase the reflected light intensity and improve the quality of the measured velocity a retro-reflective tape is bonded to the measurement points. The ultrasonic waves are measured over 200?s with a sampling frequency of 2.56 MHz. A bandpass filter is applied for signal enhancement by reducing noise outside the signal bandwidth. The results from the experiments are shown to compare favorably with those from the simulations.

10170-62, Session 9B

Developing a passive-active optical array for structural health monitoring of plate like structures

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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 their sensitivity to small defects in the structure. Traditionally they are actuated and sensed by piezoelectric transducers. In recent years, the fiber Bragg grating (FBG) sensors have emerged as embeddable candidates for guided wave SHM toward composite structures. The FBG sensors work on converting the optical filtering changes into actual strain readings. Significant advances have been made such that the FBG sensors are now able to detect guided waves with strain amplitudes up into the MHz range.

In this paper, a passive-active optical array is built using FBG sensors with piezoelectric wafers as the wave actuators. An array tuning algorithm was developed in order to receive directional incoming waves toward the FBG arrays; followed with an imaging algorithm to map the plate-structure covered by the passive-active array network. Numerical study was performed to characterize the directional beamforming of the FBG array, in regards to array parameters as well as structural parameters. The well-known directional sensitivity of FBG sensors is considered and studied its effects on the beamforming. The algorithms are then applied to solve damage detection problems on plate-like structures in a laboratory setup. Intensity images are generated to indicate the presence and locations of simulated surface defects as highlighted areas. Future works are suggested in order to meet the SHM and damage detection needs in realistic structures.

10170-63, Session 9B

Local numerical modelling of ultrasonic guided waves in linear and nonlinear media

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Nonlinear ultrasonic techniques provide improved damage sensitivity compared to linear approaches. The combination of attractive properties of guided waves, such as Lamb waves, with unique features of higher harmonic generation provides great potential for characterization of incipient damage, particularly in plate-like structures. Nonlinear ultrasonic structural health monitoring techniques use interrogation signals at frequencies other than the excitation frequency to detect changes in structural integrity. Signal processing techniques used in non-destructive evaluation are frequently supported by modelling and numerical simulations in order to facilitate problem solution. This paper discusses known and newly-developed local computational strategies for simulating elastic waves, and attempts characterization of their numerical properties in the context of linear and nonlinear media. A new numerical approach – combining advantages of the Local Interaction Simulation Approach (LISA) and Cellular Automata for Elastodynamics (CAFE) – termed CALISA is proposed. The iteration equations of the method are derived directly from physical principles

employing stress and displacement continuity, leading to an accurate description of the propagation in arbitrarily complex media. Numerical analysis of guided wave propagation, based on the newly developed CALISA approach, is presented and discussed in the paper for linear and nonlinear media.

10170-64, Session 10A

Nonlinear ultrasonic assessment of fracture properties of asphalt mixtures

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The detrimental effects of aging of asphalt concrete materials on the cracking performance of asphalt pavements has long been recognized. Asphalt concrete continuously tends to become oxidized, leading to material embrittlement with time, reducing the resistance of asphalt mixtures against crack formation. Asphalt mixtures exhibit increasingly nonlinear response with oxidative aging. This nonlinear behavior is attributed in part due to the mesoscopic nature of the asphalt material when unaged, and at later ages to the development of a diffuse micro-flaw population. The nonlinear behavior itself follows a nonlinear trend. The nonlinear acoustic method has been demonstrated to be a quick, reliable, and non-destructive testing method for in-situ characterization of damage in asphalt concrete. The method is truly non-destructive in that no coring is necessary.

This study evaluates the oxidative aging of asphalt mixtures through conducting nondestructive as well as fracture performance tests and investigates the possibility of estimating low temperature fracture properties of aged mixtures using a nonlinear ultrasonic approach. Asphalt mixture samples, oven-aged for 12, 24, 28, 32, and 36 hours at 135 oC, were compacted, fabricated into test specimens and evaluated using a non-collinear wave mixing approach. In addition, embrittlement temperature and fracture energy of replicate samples were assessed using the acoustic emission test and disk-shaped compact tension test. Comparison of results from these three testing methods clearly demonstrated similar trends in their results. This suggests the possibility of estimating the fracture properties of mixtures from the non-collinear ultrasonic wave mixing approach, which is a truly nondestructive method.

10170-65, Session 10A

Early stage damages quantification in composites using nonlinear modulation technique

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Nonlinear damage in the composite materials is developed with the growth of damages in the material under fatigue loading. Nonlinear ultrasonic techniques are sensitive to early stage damages such as, fiber breakages, matrix micro-cracking, and deboning etc. Here, in this work, early stage damages are detected in Unidirectional (UD) carbon fiber composite under fatigue loading. Specimens are prepared according to American Society for Testing and Materials (ASTM) standard. Specimens are subjected to low cycle high load (LCHL) fatigue loading until 150,000 cycles. Sensors are mounted on the specimen used for actuation and sensing. A five count tone burst with low frequency (fc =375 kHz) followed by high frequency (fc =770 kHz) signal, was used as actuation signal. Pitch-catch experiments are collected at the interval of 5,000 cycles. Sensor signals are collected for various excitation voltage (from 5V to 20V, with 5V interval). First Fourier Transform (FFT) of the sensor signals are performed and side band frequencies are observed at around 770 kHz. Severity of damages in the material is quantified from the ratio of amplitude of side band frequencies with the central frequency. Nonlinearity in the material due to damage development is also investigated from the damage growth curve obtained at various excitation amplitude. Optical Microcopy imaging were also performed at the interval of 5,000 to examine developments of damages inside the material. This study has a good potential in detection of early stage damages in composite materials.

10170-66, Session 10A

A three-dimensional analytical model for interpreting contact acoustic nonlinearity generated by a breathing crack in plate

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Extending a two-dimensional analytical framework developed previously for studying contact acoustic nonlinearity (CAN) arising from a fatigue crack in a beam-like structure, this study reports on an analytical model to interpret CAN introduced to propagating guided ultrasonic waves (GUWs) under the modulation of a breathing crack in a plate. The breathing crack is considered, in a three-dimensional (3D) manner, as a second source to excite additional wave field. Thorough investigation of the interaction between probing GUWs and breathing crack leads to explicit, analytical and full-field description of the additional wave field. In conjunction with the use of an elasto-dynamic method, the influence of reflected and diffracted waves by the crack on the motion of crack surfaces is scrutinized quantitatively, yielding accurate depiction of the “breathing” behavior of the crack that is beneficial to quantifying crack-induced nonlinearity in GUWs (i.e. second harmonic generation). A nonlinearity index is defined to calibrate the severity of the breathing crack. Results obtained from the 3D model are compared with those from finite element simulation, to observe good agreement. Notably, this model does not request a benchmarking process against baseline signals for crack evaluation.

10170-67, Session 10A

Fatigue crack detection by nonlinear spectral correlation with a wideband input

Peipei Liu, Hoon Sohn, KAIST (Korea, Republic of)

Due to crack-induced nonlinearity, ultrasonic wave can distort, create accompanying harmonics, multiply waves of different frequencies, and, under resonance conditions, change resonance frequencies as a function of driving amplitude. All these nonlinear ultrasonic features have been widely studied and proved capable of detecting fatigue crack at its very early stage. However, in noisy environment, the nonlinear features might be drown in the noise, therefore it is difficult to extract those features using a conventional spectral density function. In this study, nonlinear spectral correlation is defined as a new nonlinear feature, which considers not only nonlinear modulations in ultrasonic waves but also spectral correlation between the nonlinear modulations. The proposed nonlinear feature is associated with the following two advantages: (1) stationary noise in the ultrasonic waves has little effect on nonlinear spectral correlation; and (2) the contrast of nonlinear spectral correlation between damage and intact conditions can be enhanced simply by using a wideband input. To validate the proposed nonlinear feature, micro fatigue cracks are introduced to aluminum plates by repeated tensile loading, and the experiment is conducted using surface-mounted piezoelectric transducers for ultrasonic wave generation and measurement. The experimental results confirm that the nonlinear spectral correlation can successfully detect fatigue crack even in a low signal-to-noise ratio condition.

10170-68, Session 10A

Numerical investigation of nonlinear interactions between multimodal guided waves and delamination in composite structures

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The prompt detection and quantification of delamination in composite structures is critical for the prevention of catastrophic failures. Ultrasonic guided waves have been investigated as a promising interrogation tool to achieve real-time passive and active structural sensing. When guided waves interact with the delamination, contact acoustic nonlinearity may arise due to the clapping of the delamination interfaces, which will introduce distinctive signal features such as higher harmonics and side-band frequency components. Thus, the nonlinear ultrasonic phenomena possess great potential to improve the delamination evaluation capability of current structural health monitoring (SHM) systems.

This paper presents a numerical investigation of the nonlinear interactions between multimodal guided waves and delamination in composite structures. The elastodynamic wave equations for anisotropic composite laminate were formulated using an explicit local interaction simulation approach (LISA). The contact dynamics was modeled using the penalty method. In order to capture the stick-slip contact motion, a Coulomb friction law was integrated into the computation procedure. A random gap function was defined for each contact pair with a distributed initial closure or opening value to approximate the nature of rough delamination interfaces. The LISA procedure was coded using the compute unified device architecture (CUDA), which enables the highly parallelized computation on powerful graphic cards. Two fundamental guided wave modes (S0 and A0) were investigated as the incident wave. Numerical case studies of different delamination locations across the thickness were carried out. The capability of different wave modes to trigger the contact acoustic nonlinearity was studied. The correlation between the delamination size and the signal nonlinearity was also investigated. Furthermore, the influence from the roughness of the delamination interfaces was also discussed. Various nonlinear ultrasonic phenomena were successfully captured during the wave delamination interactions, including the generation of nonlinear higher harmonics, side-band frequency response, and nonlinear threshold behaviors. The numerical investigation shows that the nonlinear features of wave delamination interactions can enhance the evaluation capability of guided wave SHM system. This paper finishes with discussion, concluding remarks, and suggestions for future work.

10170-69, Session 10A

Analysis of debonding in single lap joints based on employment of ultrasounds

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In this study the non-linear content of the structural response of samples of single lap joint (SLJ) subjected to ultrasonic harmonic excitation was evaluated to identify and characterise the defects within the bonded region. Different parameters such as frequency, shape, and amplitude of the response signal coming back from the adhesive joint are key criteria for understanding the quality of the adhesion. Different metallic samples with the same geometry were experimentally tested: the defects were artificially introduced bonding partially two plates and changing the extension of the debonded region. Two piezoelectric sensors (one exciting, one receiver) were attached on each of the two bonded plates. In this way, different experimental tests were carried out in order to characterise the debonding in each sample of SLJ, evaluating the generated signals feeding with the different voltage amplitudes and frequency the exciting sensor and acquired by the receiver one. The structural dynamic response of the debonded samples was found rich of components. Together with the harmonic response due to the excitation, other non-linear contributions were identified: higher harmonics (2nd, 3rd) and subharmonics. These contributions are clearly due to non-linear effects induced by the “kissing bond” and, more generally, by contact problems. Numerical models, for each SLJ, were developed in Ansys introducing non-linear contact elements, related to the defect area, and applying the harmonic excitation: the numerical data were used to validate the experimental results and to find correlation between the non-linear content of the signals and the defects of the adhesive joint.

10170-70, Session 10B

Spectral element method implementation on GPU for Lamb wave simulation

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Parallel implementation of the time domain spectral element method on GPU (Graphics Processing Unit) is presented. The proposed spectral element method implementation is based on sparse matrix storage of local shape function derivatives calculated at Gauss–Lobatto–Legendre points. The algorithm utilizes two basic operations: multiplication of sparse matrix by vector and element-by-element vectors multiplication. Parallel processing is performed on the degree of freedom level. The assembly of resultant force is done by the aid of a mesh coloring algorithm. The implementation enables considerable computation speedup as well as a simulation of complex structural health monitoring systems based on anomalies of propagating Lamb waves. Hence, the complexity of various models can be tested and compared in order to be as close to reality as possible by using modern computers. A comparative example of a composite laminate modeling by using homogenization of material properties in one layer of 3D brick spectral elements with composite in which each ply is simulated by separate layer of 3D brick spectral elements is described. Consequences of application of each technique are explained. Further analysis is performed for composite laminate with delamination. In each case piezoelectric transducer as well as glue layer between actuator and host structure is modeled.

10170-71, Session 10B

On the assumption of transverse isotropy of a honeycomb sandwich panel for NDT applications

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Due to their excellent strength-to-weight ratio, honeycomb sandwich panels are more and more used in lightweight structures, in particular in the aeronautic industry. Delaminations of individual plies in the composite skins or disbonds of a layer in the multi-layer plate structures often remain undetected. Using guided ultrasonic waves, such hidden defects can be detected. For the successful application of ultrasonic nondestructive testing methods, wave propagation characteristics have to be understood. Recently developed semi-analytical frameworks allow for the calculation of dispersion characteristics for many materials. However, the elastic material behavior is often simplified for these calculations. For example, woven composite laminates are modeled as a homogeneous transverse isotropic plate. While these simplifications only lead to minor errors, the modeling of aluminum honeycomb core sandwich panels with homogeneous transverse isotropic layers has yet to be validated.

Therefore, an efficient numerical approach is applied to determine the

dispersion characteristics of a honeycomb sandwich panel with and without simplified material behavior. A full 3D-model, including the honeycomb cells, of a small segment of the material is generated using finite elements, and the resulting dispersion curves are compared to the ones obtained by assuming homogeneous transverse isotropic layers. In addition to dispersion curves, the displacement fields of the waves are also studied.

10170-72, Session 10B

Nonlinear dispersion effects in elastic plates: numerical modelling and validation

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Nonlinear features of elastic wave propagation have attracted significant attention recently. The particular interest herein relates to complex wave-structure interactions, which provide potential new opportunities for feature discovery and identification in a variety of applications. Due to significant complexity associated with wave propagation in nonlinear media, numerical modelling and simulations are employed to facilitate design and development of new measurement, monitoring and characterization systems. However, since very high spatio-temporal accuracy of numerical models is required, it is critical to evaluate their spectral properties and tune discretization parameters for compromise between accuracy and calculation time. Moreover, nonlinearities in structures give rise to various effects that are not present in linear systems, e.g. wave-wave interactions, higher harmonics generation, synchronism and – recently reported – shifts to dispersion characteristics.

This paper discusses three local computational models for wave propagation in nonlinear media, namely the Local Interaction Simulation Approach (LISA), Cellular Automata for Elastodynamics (CAFE) and a new CALISA approach combining the first two methods. The methods are investigated in the context of their accuracy for predicting nonlinear wavefields, in particular shifts to dispersion characteristics for finite amplitude waves and secondary wavefields. Numerical results are validated against analytical calculations based on a perturbation-based solution to the nonlinear Rayleigh-Lamb problem for guided waves in plates. Critical modes – i.e., modes determining accuracy of a model at given excitation frequency – are identified and guidelines for numerical model parameters are proposed.

10170-73, Session 10B

Coupled electromechanical modeling of piezoelectric transducers for collimated beam generation

Vamshi K. Chillara, Cristian Pantea, Dipen N. Sinha, Los Alamos National Lab. (United States)

Piezoelectric transducers are widely employed for a variety of acoustic/ultrasonic sensing and imaging applications. The frequency-dependent vibration response of these transducers characterize the ultrasonic wave propagation in solid/fluid media and ultrasonic beam generation. Minimization of ultrasonic beam-spread due to diffraction and side lobe reduction is of particular importance to imaging applications. A highly collimated beam is desired especially when the beam propagation is through a highly attenuating medium. The present work aims to study the collimated beam generation in fluids from a numerical standpoint. First, we adopt a coupled electromechanical modeling approach to study the vibration characteristics of piezoelectric transducers. Then, we study low-frequency ultrasonic wave propagation in fluids and highlight some important transducer design considerations that aid collimated beam generation. Finally, we present some preliminary experimental results.

10170-74, Session 10B

Tunability of phononic crystal through mechanical buckling and contact

Ronghao Bao, Weiqiu Chen, Zhejiang Univ. (China)

Phononic crystals (PCs) have attracted plenty of attention during the past two decades, and a lot of work has been devoted to the numerical, theoretical and experimental analysis of the band gaps of the PCs with 1D, 2D and 3D structures, respectively. The band gaps have been found to be related to the topology of the unit cell, filling ratio, contrast of the material properties between matrix and inclusion, and so on. However, they are fixed when the fabrication of corresponding devices is finished in most cases. Usually, biasing fields (e.g. initial stress, initial deformation, pre-existing electric field, external electric field and magnetic field, etc.) can be utilized to tailor the band gaps in flexible and reconfigurable ways. Recently, the instability-induced deformations triggered by external mechanical loadings have been found to be an effective and reversible way to tune the band gaps and the directionality of PCs made from soft materials, such as silicon and rubber. In this project, a novel design of PCs will be proposed, which consists of perforated plate with some individual beams fixed on the boundary of internal holes. When the external mechanical loading applied on the PCs reaches a threshold value, instability-induced buckling will be triggered and the internal beams might be in contact with each other, which will significantly alter the topology of PCs, and therefore effectively tune the band gaps of PCs. A systematical analysis will be carried out to study the influences on the tunability of PCs with different designs through finite element methods (FEM).

10170-75, Session 10B

Wave propagation in perioidc dielectric elastomer beam under finite deformation

Weiqiu Chen, Zhejiang Univ. (China)

We propose a compressible soft active periodic structure to study the real time control ability or tunability of longitudinal elastic waves in it in terms of pre-deformation induced by a mechanical or electric biasing field. The simple and generalized nonlinear superelastic material model for compressible soft active materials is employed to theoretically investigate the mechanically or electrically tunable properties of band structures. The effective acoustic impedance difference is introduced which seems to be the dominating parameter in tuning the acoustic band gaps.

10170-76, Session 11A

Reflective SOA-based fiber Bragg grating ultrasonic sensing system with two wave mixing interferometric demodulation

Heming Wei, Sridhar Krishnaswamy, Northwestern Univ. (United States)

An intelligent fiber Bragg grating (FBG) ultrasonic sensing system based on a reflective semiconductor optical amplifier (RSOA) is presented for acoustic emission detection. The FBG and the RSOA laser compose an adaptive laser source, and the output is demodulated by an adaptive photorefractive two wave mixing (TWM) wavelength demodulator without any active compensation. The experimental results show that the proposed FBG ultrasonic sensing system can respond the ultrasonic waves with a frequency of megahertz, which is suitable for detecting ultrasound generated by cracking or impact loading.

10170-77, Session 11A

Continuum development of acoustic emission source modelling of cracks

Roshan Joseph, Md. Yeasin Bhuiyan, Victor Giurgiutiu, Univ. of South Carolina (United States)

This paper presents a continuum mechanics formulation for a growing crack tip source of acoustic emission. The development starts by formulating the reciprocity theorem of a continuum. By using the elastrodynamic green functions the displacement field due to body force throughout the volume of the continuum for boundary conditions on the surface is formulated. The displacement discontinuity across a newly formed crack surface is imposed as the surface boundary conditions in the formulation. The term moment tensor density is introduced in the formulation of displacement field in terms of the displacement discontinuity across the newly formed crack. The moment tensor density is integrated across the crack surface to obtain the corresponding moment tensor. The displacement field throughout the volume is then formulated by using the moment tensor. The moment tensor can be used as the source representation of a specific crack. It is a representation of excitation due to newly formed surfaces because of the crack propagation. The moment tensor formulation for a mode 1, mode 2 and mode 3 crack formation is then discussed.

10170-78, Session 11A

Probabilistic location estimation of acoustic emission sources in isotropic plates with one sensor

Arvin Ebrahimkhanlou, Salvatore Salamone, The Univ. of Texas at Austin (United States)

This paper presents a probabilistic acoustic emission (AE) source localization algorithm in isotropic plate structures. The proposed algorithm requires only one sensor and uniformly monitors the entire area of the plate without any blind zones. In addition, it takes a probabilistic approach and estimates the localization uncertainty. The algorithm obtains the information pertaining to the location of the source based on 1) edge reflected late arrivals of the emitted guided ultrasonic waves (GUW), 2) their multimodal characteristics, 3) their dispersive nature. The algorithm first estimates the distance between the source and the sensor. Then, it uses the estimated distance and edge reflected late arrivals to localize the source. In the first step, continuous wavelet transform (CWT) is used. For each frequency, the arrival time is measured for the first arrival of the two fundamental Lamb wave modes. A total least squares (TLS) estimation problem is formed based on the measurements and group velocity dispersion curves. The systematic uncertainty of the CWT is propagated with unscented transform (UT) to estimate the noise in the TLS problem. Based on the estimated noise, the TLS problem is solved and the Cramer-Rao lower bound on its uncertainty is calculated. For the second step, an analytical model is proposed to take the TLS estimation as an input and simulate the late arrivals. The other inputs to the model are the first arrivals waveforms, phase velocity dispersion curves, and a guess for the location of the source. The best guess for the source location is found based on the correlation between the simulations and the actual AE signal. Finally, the uncertainty in the distance estimation is propagated the uncertainty in the location estimation with the Monte Carlo simulations. A confidence contour for the estimated source location is calculated using the kernel density estimation (KDE) technique. The approach is validated using standard pencil lead break (PLB) test on an Aluminum plate, and promising results are achieved.

10170-79, Session 11A

Physics of materials based understanding of acoustic emission waveforms from fatigue cracks

Md. Yeasin Bhuiyan, Jingjing Bao, Banibrata Poddar, Victor Giurgiutiu, Univ. of South Carolina (United States)

Acoustic emission (AE) monitoring technique is a well-known approach in the field of NDE/SHM. AE monitoring from the defect formation and failure in the materials were well studied by researchers. However, conventional AE monitoring techniques are predominantly based on statistical analysis. In this study we focus on understanding the AE waveforms from the fatigue crack growth using physics based approach. The growth of the fatigue crack causes the acoustic emission in the material that propagates in the structure. One of the main challenges of this approach is to develop the physics based understanding of the AE source itself. The acoustic emission happens not only from the crack growth but also from the interaction of the crack lips during fatigue loading of the materials. As the waveforms are generated from the AE event, they propagate and create local vibration modes along the crack faces. Fatigue experiments were performed to generate the fatigue cracks. Several test specimens were used in the fatigue experiments and corresponding AE waveforms were captured. The AE waveforms were analyzed and distinguished into different groups based on the similar nature on both time domain and frequency domain. 3-D Harmonic Finite Element (FE) analyses were performed to identify the local vibration modes and the experimental results were used to verify the simulated results.

10170-80, Session 11B

High frequency guided wave propagation in monocrystalline silicon wafers

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Monocrystalline silicon wafers are widely used in the photovoltaic industry for solar panels with high conversion efficiency. The cutting process can introduce micro-cracks in the thin wafers and lead to varying thickness. High frequency guided ultrasonic waves are considered for the structural monitoring of the wafers. The anisotropy of the monocrystalline silicon leads to variations of the wave characteristics, depending on the propagation direction relative to the crystal orientation. The phase velocity (slowness) and skew angle of the two fundamental Lamb wave modes (first anti-symmetric mode A0 and first symmetric mode S0) for varying propagation directions relative to the crystal orientation were measured experimentally. Selective mode excitation was achieved using a contact piezoelectric transducer with a custom-made wedge and holder to achieve a controlled contact pressure. The out-of-plane component of the guided wave propagation was measured using a noncontact laser interferometer. Good agreement with the theoretical predictions based on nominal material properties of the silicon wafer was found. Preliminary measurements demonstrate that this can be employed to characterize wafer thickness and to detect defects.

10170-81, Session 11B

Studying the effects of delamination on wave propagation behavior in integrated circuit packages and defect detection using guided waves

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A key component of an integrated circuit (IC) package is the substrate, which consist of alternating layers of copper conductors built up on epoxy dielectric layers which are laminated on to a fiber glass epoxy matrix core and held together by mechanical adhesion. However, failure in mechanical adhesion may occur due to the presence of residual moisture, foreign material or insufficient copper roughening, causing delamination between the layers. The presence of delamination, due to manufacturing induced defects or other loading conditions, can lead to structural degradation and failure. In this paper, we develop a structural health monitoring (SHM) technique using guided wave propagating through a large form factor IC package to detect delamination. Piezoelectric transducers will be used as actuators and sensors for selective generation of lamb wave modes and data collection. Matching pursuit decomposition (MPD) algorithm will be used to extract the associated Lamb wave features such as time of flight, relative amplitude and presence of mode conversions. Next, the effect of presence of Delamination on the wave propagation behavior will be studied. Sensor signals obtained from the damaged specimens will be analyzed using MPD to understand the effect of delamination size and location on the Lamb wave propagation behavior. This information will be used to develop a robust damage localization methodology.

10170-82, Session 11B

Combined vibration- and guided wave-based approach for composite panels health assessment

Maciej Radzienski, Pawel Kudela, The Szewalski Institute of Fluid-Flow Machinery (Poland); Maosen Cao, Hohai Univ. (China); Wieslaw M. Ostachowicz, The Szewalski Institute of Fluid-Flow Machinery (Poland) and Warsaw Univ. of Technology (Poland)

Various NDT methods have been developed to extract information about state of a structure. Two of them: vibration-based and guided wave-based techniques are one of the most common and well developed. Both approaches can be implemented using Scanning Laser Doppler Vibrometer measurements and excitation by means of PZT transducer. In this paper authors present a combined approached for NDT using successive and simultaneous measurement of both mode shapes and full wave fields. Vibration-based damage detection is focused on detection of mode shape singularity, created by material discontinuity. This method utilizes wavelet transform for damage indication. Guided wave-based damage detection uses propagating elastic wave energy variation on the specimen surface as well as any changes in wave propagation pattern due to its interaction with material discontinuity as a tool for damage assessment. Combining this two different techniques can give higher accuracy in damage detection and assessment. At the same time any additional specimen preparation are necessary, any set-up changes are required and the all the data can be registered in the same amount of time (simultaneous excitation). To confirm proposed technique a CFRP specimen with Teflon tape insert, simulating delamination is tested. A comparison between both techniques with combined approach is presented.

10170-83, Session 11B

Numerical modeling of the load effect on PZT-induced guided wave for load compensation of damage detection

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Guided wave-based structural health monitoring (GWSHM) has been given considerable attention and widely studied for large-scale aircraft structures, especially for composites. Nevertheless, it is difficult to apply GWSHM systems on board or online, for which one of the most serious reasons is the environmental influence. Load is one fact that affects not only the host structure, in which guided wave propagates, but also the PZT, by which guided wave is transmitted and received. In this paper, a three layer spectral element including the PZT, the adhesive and the host structure is used to transmit and receive guided wave in structures by using the time spectral finite element method (SFEM), which can reduce the simulation cost of PZT-induced guided wave. The static loads with different grades are considered in the SFEM to analyze its effect on guided wave signals that PZT transmits and receives. Based on the variation trend of guided waves versus load, a load compensation method is developed to eliminate effects of load in the process of damage detection for large-scale composite structures. The probabilistic reconstruction algorithm based on the signal variation of transmitter-receiver path is employed to identify the damage in composites. Numerical and experimental tests are both conducted to verify the feasibility and effectiveness of the given method.

10170-84, Session 12A

Using prospect theory to develop a decision support system for a bridge under continuous monitoring

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The necessity to make choices is an important component of our life. In structural health monitoring, agents face decision-making problems every day but are often conditioned by psychological biases and heuristics. Management of structures does not allow mistakes, because the consequences may be deaths or injuries. We demonstrate there exists a mechanical model formally equivalent to the mathematical formulation of rational thinking: plausibility corresponds to stiffness, uncertainty to flexibility, expectation to equilibrium state, and rational thinking to conservative system. In the case of multiple parameter estimation, the analogy reads: the covariance matrix of the N uncertain parameters corresponds to the flexibility matrix of an N degrees-of-freedom equivalent mechanical system, while the exponent of the multivariate Gaussian posterior distribution of the parameters is the elastic potential energy. The Fisher information corresponds to the stiffness matrix easily obtained by calculation of the Hessian of the elastic potential energy, and the posterior mean values of the parameters correspond to the equilibrium state of the mechanical system. In principle, we can reproduce any logical inference and decision problem with a finite element model and make a judgment by finding its equilibrium state. The expected impact of an action can be seen, in the mechanical analogous, as set of mechanical elements whose potential perturbs the equilibrium state of the original system. We conclude this paper with an application of our mechanical analogous to a real-life case study in which we model the rational thinking of a hypothetical agent facing major choices concerning a monitored structure.

10170-85, Session 12A

A multi-objective evolutionary optimization approach to identifying structural damage under uncertainty

Pei Cao, David Yoo, Jiong Tang, Univ. of Connecticut (United States)

The structural damage identification is crucial in engineering practices because it can protect the structure from catastrophic failures. During the last decades, extensive research has been conducted on non-destructive damage detection techniques based on the changes of modal parameters. In this research, we make use of the multiple damage location assurance criterion (MDLAC) to characterize the correlation between the analytical predictions of the frequency changes and the measured frequency

changes. The damage location and severity can be obtained with only a few measurements by maximizing the MDLAC value. Meanwhile, the uncertainties are treated as interval uncertainties whose distributions are unknown due to limited amount of measurements. A MDLAC function is associated with each combination of interval uncertainties. Thus, by considering different combinations, a multi-objective optimization problem based on their MDLAC values can be formulated and optimized by applying the multi-objective evolutionary algorithm based on decomposition (MOEA/D) whcih treats each interval combination as a sub-problem and solves these sub-problems simultaneously by evolving a population of solutions. The proposed approach offers practical attractions of only requiring a small amount of measurements and obviating the need to assume uncertainty distributions. Finally, the proposed approach is applied to several test problems.

10170-86, Session 12A

Comparison of least square support vector machines and Kriging surrogates in probability-based damage detection of structures

Mohammad N. Noori, California Polytechnic State Univ., San Luis Obispo (United States)

Despite advances in computer capacity, the enormous computational cost of running complex engineering simulations makes it impractical to rely exclusively on simulation for the purpose of structural health monitoring. To cut down the cost, surrogate models, also known as meta-models, are constructed and then used in place of the actual simulation models. However, uncertainties existing in the measured vibration data may lead to false or unreliable output results from such models. In this study, an efficient approach based on Monte Carlo simula-tion is proposed to take into account the effect of uncertainties in developing a surrogate model. By considering dynamic behavior of a structure as input variables, two effective meth-ods of surrogate model, Least Square Support Vector Machines (LS-SVMs) and Kriging, are constructed, trained and tested to detect the location and severity of damage in civil struc-tures. The effects of using different severity levels and noise levels on the damage detection results are discussed. The proposed strategy is implemented on two examples in the field of structural damage detection. The simulation results show the proposed method can perform well in probability-based damage detection of structures with less computational effort com-pared to direct finite element model.

10170-87, Session 12A

Monitoring strength development in cementitious material using embedded piezo-transducers

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An embedded piezoelectric based Lead Zirconate Titanate (PZT) transducer is developed to monitor the early age progression of hydration and development of properties of cementitious material. The setting behavior of cement mortar is monitored continuously by analyzing the electromechanical (EM) conductance response of embedded transducer. The efficacy and sensitivity of the embedded sensor is then assessed by using mortar mixes with accelerator and retarder. The evolving mechanical impedance of the cementitious material is extracted from the coupled electromechanical response of the transducer. The extracted mechanical impedance of the embedded transducer is shown to sensitively reflect the progressive change in the stiffness of the mortar material as it transforms from fluid to solid state.

10170-88, Session 12A

Mapping and modeling of urban thermal radiation

Masoud Ghandehari, New York Univ. (United States)

A study was carried out measuring the surface temperatures of buildings stretching for eight miles along the West Side of Manhattan in New York City. This was followed by modeling the surface thermal radiation of two sample blocks having different construction densities. The measurements were done using a long-wave hyperspectral imager with 128 spectral bands, providing a spatial resolution of one meter, temporal resolution of three minutes and sub-kelvin degree accuracy. This was achieved by the derivation of the emissivity, a mixture of physical and geometrical characteristics of the surfaces. The atmospheric effects were corrected for and surface temperatures were compared with the modeled temperatures. For the modeling, we used the digital surface map of NYC, and considered a geometrically structured two-dimensional surface composed of joined polygons. Each polygon was characterized by an emissivity, surface thickness, and thermal conductivity. On the inside of the surface a local equilibrium temperature was assumed. The equilibrium temperatures on the outside surfaces were computed and determined by equating the internal and external net flux densities for each polygon. This calculation included sum of the incoming fluxes from the sky and those scattered from all other visible polygons, as well as the heat radiated by the surface. Results comparing the measured and the modeled temperatures will be presented.

10170-89, Session 12B

Application of the normalized curvature ratio to an in-service structure

Kaitlyn S. Kliewer, Branko Glisic, Princeton Univ. (United States)

Fiber optic sensors (FOS) offer numerous advantages for structural health monitoring. In addition to being durable, lightweight, and capable of multiplexing, they offer the ability to simultaneously monitor both static and dynamic strain. FOS also allow for the instrumentation of large areas of a structure with long-gages sensors which helps enable global monitoring of the structure. Drawing upon these benefits, the Normalized Curvature Ratio (NCR), a curvature based damage detection method, has been developed. This method utilizes a series of long-gage fiber Bragg grating (FBG) strain sensors for damage detection of a structure through dynamic strain measurements and curvature analysis. While dynamic SHM methods typically rely upon frequency and acceleration based analysis, it has been found in the literature that strain and curvature based analysis may be a more reliable means for structural monitoring. Previous research was performed through small scale experimental testing and analytical models, which provided promising results for the NCR as a potential damage sensitive feature. Based on this success this research focuses on the application of the NCR to an existing in-service structure, the US202/NJ23 highway overpass located in Wayne, NJ. The overpass is currently instrumented with a series of long-gage FBG strain sensors and periodic strain measurements for dynamic events induced by heavy weight vehicles have been recorded for greater than 5 years. This research shows encouraging results and the potential for the NCR to be used as a simplistic metric for damage detection using FBG strain sensors.

10170-90, Session 12B

Effect of out-of-plane specimen movement on the accuracy of the smallest specimen strain measurable using the digital image correlation technique

Joel R. Poling, Niranjan Desai, Purdue Univ. Northwest (United States)

Structural health monitoring (SHM) helps engineers maintain structures, enhance their safety, and operate them cost-effectively. Digital image correlation (DIC) techniques applied to SHM are non-contact techniques; they are also fast, accurate, and simple to implement. The goal of this investigation was to determine the smallest strain accurately measurable by a state-of-the-art DIC – based tool, in a specimen subjected to out-of-plane movement. This industry-affiliated study was motivated by initially undetected damage at low strains in connections of a real-world bridge, whose detection would have prevented its propagation, resulting in lower repair costs. The investigation builds upon an initial study, which determined the smallest accurately measurable strains using the same DIC-based tool in a specimen that was not subjected to controlled out-of-plane specimen movement. It was observed in this initial study that the minute out-of-plane specimen movements that inadvertently occurred even in the controlled conditions of the laboratory created noise in the DIC-based strain measurements. Hence, before implementing this technique in a real structure, it is desirable to determine the bounds of out-of-plane displacement of the system within which it is practical to use this technique to measure strain. A cantilevered plate specimen was transversely loaded in the laboratory, and the longitudinal strain was measured at a selected location at different values of out-of-plane displacement of the specimen, using the DIC-based tool. DIC-based strains were compared against those measured by conventional strain gauges. The smallest strain accurately measurable using DIC techniques, over a range of specimen out-of-plane displacement amplitudes, were determined.

10170-91, Session 12B

Uncertainty quantification of phase-based motion estimation on noisy sequence of images

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Optical measurements and motion estimation from a sequence of images could be considered as one of the most recent sensing methods for structural dynamics developed in the last decade. As a modern non-contact sensing technology, optical measurements could provide a full-field response without any mass loading effect or change of stiffness in structures, which is unavoidable using other conventional transducers (e.g. accelerometers, strain gages, etc.) The phase-based motion extraction is one of the most reliable methods for movement measurement, which has been gaining attention lately. However, contamination of the sequence of images with numerous sources of noise is inevitable, and the performance of the phase-based motion estimation could be affected due to the lighting changes. Within this context, the uncertainty quantification of the phase-based motion extraction is investigated in this work. Furthermore, an analytical solution is provided in order to propagate the uncertainty from the acquired images to the estimated motion. In the end of the paper, the solution is validated via Monte-Carlo simulations using both simulated and experimental data. By adopting the order statistics of the noise contamination in the sequence of images as the input, the analytical solution provided in this paper is able to predict the uncertainty bounds of the extracted motion by means of phase-based algorithm.

10170-92, Session 12B

Comparison of optimal sensor placement techniques for damage detection on a highway bridge

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Optimal Sensor Placement (OSP) is the field of automatically locating sensors to optimize the measurements using a limited number of sensors. This is important, as the number of potential monitoring degrees-of-freedom (DOF) are typically significantly more than the number of available monitoring sensors. There are many different established techniques to locate the limited number of available sensors, including the effective independence method, the effective independence driving point residue method, and the modal kinetic energy method. The different OSP methods optimize various measurement properties, such as the measured mode shapes linear independence, or the kinetic energy of the measurements. One of the goals of structural health monitoring (SHM) is to detect and quantify the damage in a structure using the vibrational measurements. In this paper, the authors shall compare the capability of different OSP techniques to quantify damage in a numerical model of the I-91 Northbound highway bridge in Meriden, CT. Damage quantification shall be performed using modal analysis of the measured response from the numerical model at the identified DOF. And, the effectiveness of the OSP techniques shall be evaluated based upon the accuracy of the damage quantification using the measurements from their sensor networks.

10170-93, Session 12B

Study on evaluation of corrosion condition of reinforcing bar embedded concrete using infrared thermal imaging camera

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In Japan, as the deterioration of a huge number of infrastructures constructed in the high economic growth period has caused a serious problem, it is an urgent problem to prolong expectancies of their service life. In order to diagnose their deterioration, it is necessary to comprehend the condition of degradation of concrete structures accurately. As a method for diagnosing the condition of degradation, the condition of corrosion of reinforcing bars embedded in concrete should be detected quickly and correctly at the early stages.

At present, there are destructive test and non-destructive test as the method for evaluating the condition of corrosion of reinforcing bar. However, the destructive test has various problems that partial damages are given for concrete structures and that the change of corrosion of reinforcing bar is not possible to evaluate over time at exactly the same place. On the other hand, the non-destructive test also has a problem that the quantitative evaluation is difficult. Therefore, the establishment of new non-destructive test has been required.

In past researches, it has been confirmed that differences of corrosion thickness in reinforcing bars affect the temperature changes at the surface of concrete specimen.

In this study, while the quantitative evaluation of the degree of corrosion in reinforcing bar was carried out to using 3D scanner which could measure the volume, coverage area and cross-sectional area, after cooling down the surface of concrete specimen embedded reinforcing bar to -40 Co with liquid nitrogen, temperature changes at the surface of concrete was measured using the infrared thermal imaging camera.

From the changes of thermal images at the surface of concrete specimen obtained using the infrared thermal imaging camera, the rate of temperature rise at the surface of concrete tended to be rapid, as the corrosion thickness was bigger. Therefore, it seems that it is possible to evaluate the situation of corrosion of reinforcing bar embedded concrete by measuring changes of the thermal images at the surface of concrete using the infrared thermal imaging camera.

10170-94, Session 13A

Quantitative evaluation of rejuvenators to restore embrittlement temperatures in oxidized asphalt mixtures using acoustic emission source location technique

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Acoustic emission (AE) is a passive inspection technique that uses acoustic waves generated within the material for defect detection and materials characterization. The effectiveness of asphalt rejuvenators in restoring aged asphalt concrete to its crack resistant state is evaluated using an acoustic emission (AE) approach. An iterative and a non-iterative acoustic emission source location method were used to determine the location of cracks (i.e., source location) inside the specimens as the temperatures lowered down to -35 oC. The embrittlement temperatures of asphalt concrete virgin samples and of samples oven-aged for 36 hours at 135 oC were observed to be -25 oC and -15 oC, respectively. Specimens oven-aged for 36 hours were then treated with rejuvenators (10% of the binder content by weight) on their top surface and tested using the same AE approach after 2, 4, 6, and 8 weeks of dwell time. It was observed that after four weeks of dwell time, the top half portion of the rejuvenated asphalt specimen has lower embrittlement temperature than the bottom half portion, and the rejuvenator-treated portion had recuperated the embrittlement temperatures of its virgin condition. It was also observed that the rejuvenator kept acting upon the binder after four weeks of dwell time. At the end of six weeks, the embrittlement temperature was observed to be homogeneous across the height of the specimens. After eight weeks the specimens had an embrittlement temperature about two grades (~12 oC) lower than that of the virgin specimen.

10170-95, Session 13A

Monitoring of prestress losses using long-gauge fiber optic sensors

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Prestressed concrete has been increasingly used in the construction of bridges due to its superiority as a building material. This has necessitated better assessment of its on-site performance. One of the most important indicators of structural integrity and performance of prestressed concrete structures is the spatial distribution of prestress forces over time, i.e. prestress losses along the structure. Time-dependent prestress losses occur due to dimensional changes in the concrete caused by creep and shrinkage, in addition to strand relaxation. Maintaining certain force levels in the strands, and thus the concrete cross-sections, is essential to ensuring stresses in the concrete do not exceed design stresses, which could cause malfunction or failure of the structure. This paper presents a novel method for monitoring prestress losses based on long-gauge fiber optic sensors embedded in the concrete during construction. The method includes the treatment of varying environmental factors such as temperature to ensure accuracy of results in on-site applications. The method is presented as applied to a segment of a post-tensioned pedestrian bridge on the Princeton University campus, Streicker Bridge. The segment is a three-span continuous girder supported on steel columns, with sensors embedded at key locations along the structure during construction in October 2009. Temperature and strain measurements have been recorded intermittently since construction. The prestress loss results are compared to estimates from design codes, which proved the conservativeness of the design.

10170-96, Session 13A

System identification of timber masonry walls using shaking table test

Timir Baran Roy, Concordia Univ. (Canada); Luis Guerreiro, Univ. de Lisboa (Portugal); Ashutosh Bagchi, Concordia Univ. (Canada)

Dynamic study is important in order to design, repair and rehabilitation of structures. It has played an important role in the behavior characterization of structures; such as: bridges, dams, high rise buildings etc. There had been substantial development in this area over the last few decades, especially in the field of dynamic identification techniques of structural systems. Frequency Domain Decomposition (FDD) and Time Domain Decomposition are most commonly used methods to identify modal parameters; such as: natural frequency, modal damping and mode shape. The focus of the present research is to study the dynamic characteristics of typical timber masonry walls commonly used in Portugal. For that purpose, a multi-storey structural prototype of such walls has been tested on a seismic shake table at the National Laboratory for Civil Engineering, Portugal (LNEC). Signal processing has been performed of the output response, which is collected from the shaking table experiment of the prototype using accelerometers. In the present work signal processing of the output response, based on the input response has been done in two ways: FDD and Stochastic Subspace Identification (SSI). In order to estimate the values of the modal parameters, algorithms for FDD are formulated and parametric functions for the SSI are computed. Finally, estimated values from both the methods are compared to measure the accuracy of both the techniques. Keywords— Frequency Domain Decomposition (FDD), modal parameters, signal processing, Stochastic Subspace Identification (SSI), Time Domain Decomposition.

10170-98, Session 13A

Abnormal behavior detection algorithm of infra-structure using unfamiliarity index

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All living organisms use memory and oblivion algorithms considering the estimated lifetime and the changes in the ambient environment. Because of the expected lifetime of a bridge is similar to the human's one, if a bridge uses the same algorithm of human memory, the abnormal responses of the structure can be easily detected. This paper introduces unfamiliarity index (UFI) that calculated from the FFT results of the short term timeline acceleration responses. If this algorithm, which can detect an abnormal behavior from the maximum constant signal, is used to the terminal sensors of a structure, more accurate safety control criteria will be prepared efficiently.

10170-99, Session 13A

Monitoring the residual strains of concrete which exposure to freeze-thaw tests

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Concrete structures which exposed in cold climates suffer damage by freeze-thaw cycles during their working life. It is very important to observe, monitor and evaluate the damage of the structures in real-time to avoid any king of major accidents or serious consequence. Recent years, lots of imaging analysis has been widely studied, for example, the air void

counting, X-ray computed tomography and digital-image-processing (DIP) technique. Although the study technology of imaging analysis is good for study the mechanism of damage, but the process is complicated and not be able to achieve real-time monitoring. In this study, the residual strains of concrete cylinders which exposure to freeze-thaw environment is monitored. The WLI (white light interferometer) sensing technique which can realize long-term and real-time monitoring is used. To monitor the residual strains, two concrete cylinders with the diameters of 100mm and 150mm high are made. A bare fiber with the length of 10 m is used to wind around the cylinder surface. After lots of freeze-thaw cycles, the residual strain of concrete cylinder generated and the bare fiber will change from its length as response. In the experiment, the data is collected every 25 freeze-thaw cycles. Experiment results have shown that the expansion strain along the bare fiber can be detected and measured by WLI. The strain monitored by optical fiber is increased with the numbers of freeze-thaw cycles, which indicated that WLI technique is suitable for residual strain monitoring in concrete freeze-thaw damage. The method which used in this study could reflect the residual strain of the whole concrete matrix and achieve real-time monitoring the damage of concrete structures.

10170-100, Session 13A

Condition assessment of steel box girder: a strain-matching-based approach

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Serving as one of the most important part of the bridges that directly bears the load of vehicle, steel box girder suffers from the fatigue damage. However, the strain response – one of the most direct indicator of the girder's condition has received the least interest. This paper conducts a study on the monitored strain of box girder and proposes a strain-matching-based approach for the assessment of steel box girder by: firstly, separating the environmental part of the strain history out and obtaining the vehicle-induced strain; secondly, matching the vehicle-induced part of several different strain gauges by the Dynamic Time Wrap based similarity; lastly, extracting features of the matched strain series and training a statistical assessment model. The matching process is intrinsically the matching of the load of vehicle, by doing this, the relationship in strain of different gauges under the same load is obtained and modeled in a statistical way, thus any change that exceed the threshold in the model parameters is considered to be the change in the condition of the girder.

10170-101, Session 13A

Development of a real-time bridge structural monitoring and warning system: a case study in Thailand

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Regarded as one of the physical aspects under societal and civil development and evolution, engineering structure is required to support growth of the nation. It also impacts life quality and safety of the civilian. Despite of its own weight (dead load) and live load, structural members are also significantly affected by disaster and environment. Proper inspection and detection are thus crucial both during regular and unsafe events. An Enhanced Structural Health Monitoring System Using Stream Processing and Artificial Neural Network Techniques (SPANNeT) has been developed and is described in this paper. SPANNeT applies wireless sensor network, real-time data stream processing and artificial neural network based upon the measured bending strains. Major contributions include an effective, accurate and energy-aware data communication and damage detection of the engineering structure. Strain thresholds have been defined according to computer simulation results and the AASHTO (American Association of State Highway and Transportation Officials) LRFD (Load and Resistance Factor Design) Bridge Design specifications for launching several warning levels. SPANNeT has been tested and evaluated by means of computer-based simulation and on-site levels. According to the measurements, the observed maximum values are 25 to 30 microstrains during normal operation. The given protocol provided at least 90% of data communication reliability. SPANNeT is capable of real-time data report, monitoring and warning efficiently conforming to the predefined thresholds which can be adjusted regarding user's requirements and structural engineering characteristics.

10170-102, Session 13A

Experimental validation of a structural damage detection method based on Marginal Hilbert Spectrum

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Structural Health Monitoring (SHM) using dynamic characteristics of structures is crucial for early damage detection. Damage detection can be performed by capturing and assessing structural responses. Instrumented structures are monitored by analyzing the responses recorded by deployed sensors in the form of signals. Signal processing is an important tool for the processing of the collected data to diagnose anomalies in structural behavior. The vibration signature of the structure varies with damage. In order to attain effective damage detection, preservation of non-linear and non-stationary features of real structural responses is important. Decomposition of the signals into Intrinsic Mode Functions (IMF) by Empirical Mode Decomposition (EMD) and application of Hilbert-Huang Transform (HHT) addresses the time-varying instantaneous properties of the structural response. The energy distribution among different vibration modes of the intact and damaged structure depicted by Marginal Hilbert Spectrum (MHS) detects location and severity of the damage. The present work investigates damage detection analytically and experimentally by employing MHS. The testing of this methodology for different damage scenarios of a simply supported steel beam and a frame structure resulted in its accurate damage identification. The sensitivity of Hilbert Spectral Analysis (HSA) is assessed with varying frequencies and damage locations by means of calculating Damage Indices (DI) from the Hilbert spectrum curves of the undamaged and damaged structures.

10170-103, Session 13B

Moisture contamination detection in adhesive layer using embedded fibre Bragg grating sensors

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The paper presents an application of embedded fibre Bragg grating (FBG) sensors for moisture contamination detection in an adhesive layer between composite elements. Due to their high corrosion resistance as well as their small size and weight FBG sensors are a great tool for Structural Health Monitoring of composite structures. Adhesive bonds are very popular in many industrial sectors (e.g. automotive, aircraft). One of the major problems limiting the use of adhesive joints is their sensitivity to water from

the ambient. Even 1% of moisture affects the adhesive bond layer strength.

The experimental and numerical investigations were performed on rectangular samples of two glass fibre reinforced composite elements bonded together using an adhesive commonly used in the bonding or repair of aircraft elements. Moisture contamination due to diffusion process changes the volumetric properties of the material induced strain. This strain was measured by FBG sensors embedded in the adhesive layer parallel to the main axis of the sample. The behavior of the adhesive layer in the analysed sample was also modeled using commercial finite element code ABAQUS.

Numerical and experimental results confirm the utility of FBG sensors for moisture detection in the adhesive layer even when the amount of moisture is around 2% of the sample weight.

10170-104, Session 13B

BIM-based structural performance assessment of individual modules for SHM sensors placement in modular building projects

Mojtaba Valinejadshoubi, Ashutosh Bagchi, Osama Moselhi, Concordia Univ. (Canada)

Modular building construction is a factory-based construction technique that the building's units, called modules, are fabricated in a manufacturing plant, then shipped to the construction site and are installed there to form a building. Modular building design is more complex than conventional one due to the additional processes needed such as manufacturing, transportation, installation etc. Therefore, modules need to be designed to resist various types of loads such as fabrication, transportation, installation and operational loads. The modular building technology is relatively new with limited understanding of structural performance under different loading conditions. Load-bearing modules typically consist of the same size of studs at the same spacing, need to be designed to withstand axial load, bending or a combination of both. The issues associated with modular construction can be the lack of proper design and management tool, the need for considering fabrication at the design phase, ability to understand and anticipate the impact of design change, etc. Hence, using an effective tool to solve these issues is vital in modular building design. Building Information Modeling (BIM), which is an objected-oriented technology, has emerged as an effective parametric design tool in modular construction industry. On the other hand, due to the different types of loads applied on the modules during their life cycle, complex nature of structural components and connections of modular buildings, and the complexity of the structural behavior of an assembly of module, using an effective monitoring tool such as Structural Health Monitoring (SHM) is vital during the life cycle of the modules.The main objective of this study is to demonstrate how BIM software technology can be utilized to increase the opportunities for assessing the structural performance of modules under different maximum expected loading scenarios in modular building design to identify the critical elements for SHM sensors placement. Furthermore, the Potential of BIM in SHM of modules is also investigated.

10170-105, Session 13B

Temperature dependence of electro-mechanical impedance based bond-line integrity monitoring

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Bonding using adhesive films has always been an advantageous joining method over conventional mechanically fastened joints for development of lightweight automotive and aerospace structures. However, lack of reliable bond-line integrity monitoring technique limits the use of bonded joints. Electromechanical impedance (EMI) based bond-line monitoring is a rapidly growing technique in structural health monitoring. Previous work on this method has focused on monitoring the EMI of the embedded transducer by changing the static and cyclic load on the adhesively bonded samples. However, an increase in the operating temperature can degrade the piezoelectric material and adhesive simultaneously. This can result in misinterpretation of EMI data acquired from the piezoelectric material regarding the bond-line integrity.

Therefore, the preliminary objective of this work is to quantify the change in the electrical impedance as a function of temperature dependent material matrix of a piezoelectric material and the adhesive. A finite element (FE) model has been developed based on theory of linear piezoelectric effect.

When the adhesively bonded samples are mechanically loaded in a high temperature environment, the load as well as the temperature changes the EMI of the piezoelectric material. In the current work, using the FE model, the signal features are investigated to decouple the effect of load and temperature on the piezoelectric material embedded in the adhesively bonded samples.

Using the temperature dependent experimental data, it is also demonstrated via the electrical impedance curve that the BS-PT piezoelectric material offers a better temperature stability over PZT-5A as the temperature is increased from 15C to 150C.

10170-106, Session 13B

Load identification sensor based on distributed fiber optic technology

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The manufacturing and preliminary numerical and experimental testing, of a fiber optic based sensor, able to recognize different load paths, is presented. This sensor is conceived to identify loads directions by strain detection along a circumferential geometry. The sample is realized by manufacturing of a circular shaped, flexible glass/epoxy laminate. Two loops of optical fiber, laying at different quote along its thickness, is opportunely integrated. The device, is supposed to be bonded onto the structural element under load and able to follow its deformations. The working principle is based on the comparison of the strain paths detected by each loop of fiber optic at homologous positions. Rayleigh backscattering optical technology is chosen for measuring deformations with high spatial resolution. The strain paths correlation is then applied for loads identification. The finite element modeling is used to simulate the sensor working modality under specific load conditions and make predictions on the optimal design.
The experimental campaign is set to assess the finite element modeling considering in plane traction and out of plane bending loads for preliminary numerical and experimental validation.

10170-107, Session 13B

Elastic band structure engineering of anti-chiral lattices for acoustic metamaterial applications

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In this work we explore the potential of using anti-chiral elastic lattices, which can be readily produced using fast additive manufacturing techniques, as dynamic components in acoustic metamaterial designs. Anti-chiral lattices have received recent attention due to their auxetic properties and relatively low Young's modulus compared to other hierarchical lattices. Through geometric engineering of the anti-chiral unit cell, we use band structure and propagation modeling to investigate a number of extraordinary acoustic propagation phenomena associated with metamaterials. These include the possibility of effective negative index, zero index, slow sound, and hyperbolic bands. Furthermore, we demonstrate that the combination of anti-chiral and non-auxetic lattices in superlattice architectures can achieve an extra degree of anisotropy tunability. Finally, an analysis of the unit cell termination is presented in order to determine potential coupling of the elastic lattices to acoustic fluids.

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10170-108, Session 13B

Excitation and reception of shear-horizontal (SH) waves by using face-shear and thickness-shear piezoelectrics: a comparative study

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The non-dispersive fundamental shear horizontal (SH0) is of practical importance in guided-wave-based inspection technique. Traditionally, the SH waves were generated by using electromagnetic acoustic transducers (EMAT) in a non-contact manner whose coupling efficiency is fairly low. In recent years, great progresses had been made in excitation of SH0 wave by using piezoelectric transducers. In this work, we will comparatively review the performances of five types of piezoelectric transducers in excitation and reception of SH waves, including thickness-shear d15 mode PZT ceramics wafer, face-shear d36 mode PMN-PT single crystal, face-shear d36 mode PZT ceramics wafer (realized by ferroelastic domain engineering), apparent face-shear d36 PZT ceramics wafer (realized via two-dimensional antiparallel poling) and the newly defined face-shear d24 mode PZT ceramics wafer. Firstly, the working principle and configurations of each kind of SH0 wave transducers were briefly introduced. Then comparative studies of these piezoelectric transducers' performance on exciting SH0 wave were performed by using both finite element simulations and experimental testing. It is found that all the five types of piezoelectric transducers can generate SH0 wave, but only the face-shear d24 mode PZT wafer can generate single mode SH0 wave. Finally, the merits and demerits of each type of piezoelectric transducer were intensively discussed.

10170-109, Session 13B

Localization of a breathing crack in stepped beams using nonlinear frequency mixing

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The nonlinear interaction of guided waves with breathing cracks generates distinct response characteristics. In an event when the interrogation signal comprises two carrier frequencies, the nonlinearity emanating from a breathing crack gives rise to multiple peaks in the frequency response spectrum. The phenomenon is referred to as the nonlinear frequency mixing, and has been well-explored experimentally. However; theoretical investigations, expositing the genesis of frequency mixing together with its use in the crack localization, are reported by a relatively few number of researchers. The paper presents an analytical-numerical framework for analyzing the interaction of a dual frequency guided wave with a breathing crack present in a stepped beam, and further elucidates the procedure of its localization based on processing the time-domain response.

To this end, a method based on wavelet spectral finite elements is outlined to simulate the propagation of a dual frequency flexural wave through stepped Euler-Bernoulli beams with a breathing crack. The local flexibility at the crack-location is modeled using an equivalent spring approach. The intermittent contact between the crack surfaces is modeled through a bilinear force acting at the nodes of the spectral finite element. Signal processing tools are used on the time-domain response to discern the waves corresponding to different frequencies. By correlating the time-separation between their arrivals at the sensor location, a systematic procedure is outlined to localize the breathing crack. A qualitative comparison of the results is made by comparing them with those obtained using a commercial FE package. An excellent agreement between the two ascertains the utility of the proposed framework.

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10171-1, Session 1

Air curtain development: an energy harvesting solution for hinged doors

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In this paper we present an innovative energy harvesting solution – air curtain device for a hinged door. The main idea of this research is to convert the repeated open/close motion of a hinged door, and provide an electricity-free air curtain. Frequently opened door entry ways have always been regarded as a major element that causes significant energy loss and contaminated air conditions in buildings. Private companies, particularly those with warehouses where the bay doors can be left open for several hours at a time, have introduced commercial electrical air curtains as way to solve this issue. By installing an electrical fan over a doorway that is frequently opened, and blowing a sheet of air downwards, these devices prevent cross contamination from outside and maintain the inside conditioned environments. This paper intends to introduce an original design of air curtain that operates fans when the door opens and closes. The average person uses door entry ways several times a day with an almost unconscious amount of applied force and effort. This leads to a high potential of energy to be harvested in doorways that see high traffic and frequent operation. The hinged door has potential to be a self-sustainable system to prevent the transfer of outside air and contaminants. We conducted research to determine the most efficient method of harvesting energy from door use and prototype process to meet the required performance of a current air curtain. The final prototype was developed as a proof of concept for the design.

10171-2, Session 1

Experimental verification and optimization of a linear electromagnetic energy harvesting device

Christopher Mullen, Soobum Lee, Univ. of Maryland, Baltimore County (United States)

The purpose of this research is to develop a simulation code for a linear electromagnetic energy harvester, verify the simulation result with experiment, and use this code to optimize the harvester design in terms of coil and magnet layout for power maximization. Electromagnetic energy harvesters scavenge energy from wasted kinematic and vibration energy in human motion. A backpack is considered as the possible mounting position for the harvester that can generate electrical energy out of vertical hip displacement during human gait. The placement of a permanent magnet based linear generator mounted in a backpack can make use of this excitation that results in relative motion of the magnet to the coil of copper wire, which induces an electric current. This current can be used to charge a battery or capacitor bank installed on the backpack to power portable electronic devices, thereby reducing the need for extra batteries and overall battery weight. In the simulation code, an in-depth study on coil inductance and resistance is investigated and implemented. We confirmed that the simulation result agrees with the experiment result. Design optimization was additionally performed based on the simulation code and the effective design for backpack application is provided.

10171-3, Session 1

A study of water electrolysis using ionic polymer-metal composite for solar energy storage

Alicia Keow, Zhihang Ye, Zheng Chen, Wichita State Univ. (United States)

Pure hydrogen gas is harvested easily through the electrolysis of water. They are feed into proton exchange membrane fuel cell (PEMFC) to produce electricity with clean emission. Ionic polymer-metal composite (IPMC) which is made from electroplating of Nafion, a proton-conductive polymer film, encourages ion migration and dissociation of water under application of external voltage. This property has been proven to be able to act as catalyze for the electrolysis of pure water. Our renewable energy system inspired by photosynthesis, uses solar panel to gather sunlight as the source of energy for generating the electricity required to activate the IPMC electrolyzer. The hydrogen gas collected are storable fuel and are converted back energy using a commercial fuel cell. This paper aims to create a round-trip energy efficient system which can harvest solar energy, store them in the form of hydrogen gas and convert the stored hydrogen back to electricity through the use of fuel cell with minimal overall losses. We discuss the effect of increasing the surface area of contact of the polymer electrolyte membrane (PEM) through etching with Argon and Oxygen towards the increase of energy conversion efficiency of water electrolysis. We also study the relationship between varying the temperature of water between 20 °C to 75 °C toward the ionic conductivity of the membrane. Experimental results show that increasing the temperature of water increases the rate of gas generation. We validate that increasing the surface area of polymer-metal interface of the IPMC increases the energy conversion efficiency of hydrogen gas production.

10171-4, Session 1

Optimized MPPT-based converter for TEG energy harvester to power wireless sensor and monitoring system in nuclear power plant

Shaoxu Xing, Isil Anakok, Lei Zuo, Virginia Polytechnic Institute and State Univ. (United States)

In order to avoid the accidents like Fukushima Disaster and monitor the operation status of nuclear power plant, a wireless sensor system which is powered by the Thermoelectric Generator (TEG) Energy Harvester is designed and built. The TEG Energy Harvester utilize the difference between the temperature of coolant pipes in nuclear power plant, which can range from 275? to 325?, and the room temperature to generate DC voltage to power the monitoring sensors and wireless communication module. The TEG Energy Harvester is designed to provide a voltage around 10V and maximum power of 2W on a matched load under the normal working conditions. By carefully designing the wireless communication module and sensors, these output would be enough to power the whole system in normal conditions.

However, when the nuclear disaster happens, the reactor will be shut down and the temperature of coolant pipe will gradually decrease to room temperature. In order to ensure that the system can continue working and providing information for a period of time even if the nuclear power plant is shut down by disasters, a power converter and energy storage unit is required. The power converter for TEG Energy Harvester to power wireless monitoring system should have a certain level of radiation-hardened ability and the capability of converting TEG Energy Harvester's output voltage to

a constant voltage as well as extracting the maximum power from it in any conditions. Considering all the requirements for the power converter and energy storage unit comprehensively, the Single-Ended Primary-Inductor Converter (SEPIC) and a Li-ion battery are chosen. Meanwhile, an optimized Maximum Power Point Tracking (MPPT) is proposed and implemented in the circuit to keep the TEG Energy Harvester outputting the maximum power in any cases.

Given the electrical model of the TEG Energy Harvester, the MPPT algorithm applied in the circuit is designed to keep the input impendence of the power converter to be equal to the internal resistance of the TEG Energy Harvester. This MPPT algorithm is optimized based on the parameters of the TEG Energy Harvester and the model of SEPIC in Continuous Conduction Mode (CCM). The optimization of this algorithm does not only ensure the good performance of the power converter in CCM, but also helps the converter to get out of the Discontinuous Inductor Current Mode (DICM), in which the SEPIC will output much less power. Due to the special characteristics of the SEPIC and the optimized MPPT algorithm, the complexity of the whole system is reduced as there is only one current sensor is used to monitor the output current. This current sensor also provides the chance for the system to detect abnormal situations of the power converter and battery. At the same time, this optimized MPPT algorithm also uses adaptive step length to track the maximum power point. Thus, a faster response can be obtained when the output power of TEG Energy Harvester suddenly changes.

A prototype of this whole system has been built and tested in different conditions. The test results shows that the system is able to sense and monitor the parameters of the coolant pipe and transfer the data through the wireless communication module. And the power converter can track the maximum output power of TEG Energy Harvester well and charge the battery in the tests. Sufficient energy can be provided to the sensors and wireless communication system during the tests.

10171-5, Session 2

Synthesis, characterization, and property investigation of polyvinylidene fluoride (PVDF)-graphene nanocomposites for energy harvesting application

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Graphene possess extraordinary electrical, mechanical and thermal properties and also have potential applications in many areas such as biosensors, conducting agent and composites. PVDF/Reduced graphene oxide (rGO) nanocomposites were prepared using in-situ solvothermal reduction of graphene oxide in the PVDF solution. The nanocomposites were prepared with different concentrations of filler. The extent of interaction is determined by Transmission Electron Microscopy. The structural changes determined by UVvisible spectroscopy and X-ray diffraction studies. Surface morphology is determined by Scanning Probe Microscopy.

Dielectric studies of pure PVDF and nanocomposites were compared over a range of frequencies (20 Hz-1MHz) and temperature 25-37oC, which shows significant improvement in dielectric constant and decrease in dielectric loss in nanocomposite as compared to pure PVDF. Electrical conductivity of the composites is also measured. Further this material is used in Energy Harvesting applications.

10171-6, Session 2

Numerical modeling and analysis of a piezoelectric transducer beam for energy harvesting using an oscillating heat pipe

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Energy Harvesting is a powerful process that deals with exploring different possible ways of converting energy dispersed in the environment into more useful form of energy, essentially electrical energy. Piezoelectric materials are known for their ability of converting mechanical energy into electrical energy or vice versa. Our work takes an advantage of piezoelectric material's properties to essentially convert thermal energy into electrical energy using an oscillating heat pipe set-up. Specific interest in an oscillating heat pipe has relevance to energy harvesting for low power generation suitable for remote electronics operation as well as low-power heat reclamation for electronic packaging.

Experimental set up has a piezoelectric patch with fixed configuration, attached inside an oscillating heat pipe and its behavior when subjected to the oscillating fluid pressure was observed. Numerical model is aimed at replicating the experiments using a multi-physics FEA software. It consists of a three-way interaction simulation that takes into account fluid-structure interaction, solid mechanics and electrical response of the harvester circuit. The aim of this paper is develop a multi-physics design and analysis model that aids in predicting electrical power generation inherent to an oscillating heat pipe. Simulation results were compared with experimental results to ensure the validity of the numerical model that estimates the generated electrical power.

10171-7, Session 2

Battery charge and health state monitoring via ultrasonic-guided-wave-based methods using built-in piezoelectric transducers

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Extensive research in lithium-ion batteries has been ongoing to further improve the amount of energy a cell can store while minimizing the weight and volume. Yet, lithium-ion batteries can only operate safely and reliably in a narrow envelop, thus demanding accurate state-estimation, control and management systems. Obtaining an accurate estimation of the battery state of charge (SoC) during real operation has always been a challenge to the battery community. Additionally, the remaining useful life of a battery, or the state of health (SoH), degrades over time and cannot be accurately in real-time due to the lack of precise laboratory electrochemistry equipment on-board the devices.

We therefore propose a novel technique for lithium-ion battery SoC and SoH inspection based on ultrasonic guided-wave techniques using low-profile built-in piezoelectric wafer transducers. We demonstrate the feasibility of the concept by performing ultrasonic-guided-wave pitch-catch using surface-mounted piezoelectric disc transducers on a lithium-ion pouch battery cell during the electrical cycling. Changes in the ultrasonic waveforms can be observed and are shown to correlate with the physical cyclic changes in the material properties of the battery as a function of charge state. The irreversible degradation of battery performance due to repeated electrical cycling is also found to cause the irreversible changes in the ultrasonic waveforms. Through time-domain analysis and cross time–frequency analysis, we also provide a framework which allows guided ultrasonic waves to be systematically used and applied to the state-of-the-art battery management system for accurate prediction of battery SoC and SoH.

10171-8, Session 2

Electrochemical behaviors of a wearable woven textile Li-ion battery consisted of a core and wound electrode fibers coated with active materials

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Increasing needs for personal and portable healthcare devices, hybrid electric vehicles, smartphones, etc. require advanced smaller and lighter batteries of high power density. Li-ion batteries provide one of the best tradeoff in terms of power density, low weight, cell voltage, and low self-discharge. In an effort to develop an advanced new Li-ion battery, a new wearable woven textile battery consisted of a core material and wound electrode and separator fibers coated with active materials was designed, fabricated, and tested throughout this study. A Matlab program based on mathematical, electrochemical, and pseudo-two-dimensional model were developed in order to analyze its performance such as voltages, ion concentration, temperature increase, current density, etc. Special cares were given to the interface boundary conditions in the three primary sections of the battery – positive and negative electrodes and the separators. For various shapes of fabric batteries, potential energy (voltage), and charge-discharge phenomena were analyzed using a mathematical battery model based on ionic transportation equations, a Butler-Volmer equation, Fick's law, a Nernst equation, etc. As a result of battery analyses, an innovative design consisting of fabric weaving fiber yarns were suggested.

10171-30, Session 2

An energy harvesting solution based on the post-buckling response of non-prismatic slender beams

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Systems based on post-buckled structural elements have been extensively used in many applications such as actuation, remote sensing and energy harvesting thanks to their efficiency enhancement.

The post-buckling snap-through behavior of bilaterally constrained beams has been used to create an efficient energy harvesting mechanism under quasi-static excitations. The conversion mechanism has been used to transform low-rate and low-frequency excitations into high-rate motions. Electric energy can be generated from such high-rate motions using piezoelectric transducers. However, lack of control over the post-buckling behavior severely limits the mechanism's efficiency.

This study aims to maximize the levels of the harvestable power by controlling the location of the snapping point along the beam at different buckling transitions. Since the snap-through location cannot be controlled by tuning the geometry properties of a uniform cross-section beam, non-uniform cross sections are examined. An energy-based theoretical model is herein developed to predict the post-buckling response of non-uniform cross-section beams. The total potential energy is minimized under constraints that represent the physical confinement of the beam between the lateral boundaries.

Experimentally validated results show that changing the shape and geometry dimensions of non-uniform cross-section beams allows for the accurate control of the snap-through location at different buckling transitions. A 78.59% increase in harvested energy levels is achieved by optimizing the beam's shape.

10171-10, Session 3

Compressive sensing for fault diagnosis of rotating parts of wind turbines

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In order to mitigate climate change effects and decentralize power generation, renewable energy sources (RES) are becoming increasingly important worldwide. Wind Turbines (WTs) are prone to failures predominantly due to the challenging operational conditions they face while in-service. As in most industrial engineering systems, failure of critical components will almost certainly result to loss of production and reduced availability and in extreme cases to severe damage or even complete loss of the WT [1].

Recently, maintenance has shifted from scheduled maintenance to condition based maintenance (CBM) and WT maintenance could not be an exception. To this end various approaches have been proposed to enhance the effectiveness of maintenance approaches and techniques employed [2].

One of the challenges for deploying CBM solutions is the difficulty in transmitting large amounts of data due to the remote locations where wind farms are constructed. The solution to that problem is either the use of on-site advanced signal processing and data storage capability or the transmission of statistically processed data. In this work we investigate the possibility of using a compressive sensing approach capable of recovering the fault related frequencies from a reduced set of transmitted data [3].

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10171-11, Session 3

Development of an embedded thin-film strain-gauge-based SHM network into 3D-woven composite structure for wind turbine blades

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In recent years of renewable energy industry, there has been increasing demand in developing low-cost, effective structure health monitoring/sensing system to be embedded into 3D-woven composite wind/marine turbine blades to determine structural integrity and presence of defects. Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for blade manufacturers and maintenance teams to reduce maintenance and re-calibration activities. Several types of traditional sensors have been investigated for SHM applications, including surfaced-mounted strain gauge, accelerometer, ultrasonic sensors, passive acoustic sensors, fibre optic sensors, or detect defects by non-destructive test methods such as x-ray scans. However, those approaches are often expensive, time-consuming and complicated to be implemented. Using embedded resistive-based strain sensory to determine the structural integrity is an effective and low-cost way of determining the health of the composite structure. With measuring the strain and temperature inside composites at both in-situ blade resin curing and in-service stages, we are developing a novel scheme to embed a resistive-strain-based thin-metal-film sensory into the blade spar-cap that is made of composite laminates to determine structural integrity and presence of defects. A variety of techniques of embedding the customized-designed thin-metal-film strain measurement sensor are investigated to ensure the composite sample load monitoring for a long period of time to meet requirements with little maintenance and re-calibration activities. Prototypes of such 2D and 3D-woven sensing composite laminates are constructed from layers of Toray fiberglass and resin prepreg using the recommended cure cycle developed in our lab. Integrating the thin-metal-film sensor within the composite laminate provides a sensing element that measures structural behaviour. Thus, with fiberglass, epoxy, and a thin-metal-film sensing element, a three-part, low-cost, smart composite laminate is developed. Analytical solutions to the loading cases are developed to validate results obtained during experiments. The delamination is specially studied as the delamination would have no effect on the sample strength during a tension test because there are no inter-laminar forces being exhibited. The composite laminate with the integrated SHM system are tested under tensile and flexural loading test standards of ASTM D3039 and D7264, respectively. Initial strain measurements on the prototype are conducted with Microstrain LORD equipment. The prototype showed hundreds of micro-strain value during the initial bending test, and C-scan picture showed this laminate is uniform as the sensor is well bonded inside the laminate. More mechanical material characteristic tests and performance at different temperature settings are to be further completed to verify the mechanical coupling at resin matrix around sensor, and determine any detrimental effect caused by embedment. Additionally, 3D-weaving methods should be analyzed to optimize the sensory capabilities. To the best of author's knowledge, the experiment is the first demonstration of embedding thin-metal-film strain-measuring sensor into composites to monitoring composite spar cap structure in both resin curing and in-service stages. Our proposed method will dramatically reduce sensing cost for renewable green energy generation.

10171-12, Session 3

Optimal statistical damage classification in an experimental wind turbine blade using minimum instrumentation

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The increasing demand for carbon neutral energy in a challenging economic environment is a driving factor for advancements in renewable energy in recent years. For the wind energy sector, potential energy outputs are enhanced by erections of ever larger wind turbines (WTs) in remote areas where wind speeds are higher and more predictable. Low masses of WT blades (WTBs) are key structural design considerations for these developments facilitated by novel composite materials. However, the WT's long-term safety and reliability is affected by higher flexibilities and lower buckling capacities of these WTBs. Additionally, intervals for condition inspections are rigidly defined by international standards and guidelines. This practice applied to large WTs in remote sites causes significantly increasing operation and maintenance costs. Effective structural health monitoring (SHM) of WTs can make a difference by scheduling maintenance actions according to the actual state and, with it, balancing the risk of failures with inspection and maintenance costs.

Vibration-based SHM methods have an edge over other available techniques due to their moderate instrumentation requirements and the applicability for continuous monitoring of complex structures in harsh environments. These advantages are results of the availability of mature sensing techniques and utilization of global vibration responses from ambient and operational excitation sources, where elastic waves encompass the entire structure due to low damping and long wave lengths. Global methods for detection of structural damages with the help of a single sensor are available, but for increasing the utility of SHM further knowledge about the damage characteristics is requested. Damage scenarios which are frequent or impose severe risks for the structure can be identified by inspection reports of existing structures or numerical simulations. Therefore, the present paper proposes a novel approach for vibration-based structural damage classification (SDC) for the application in WTBs. The method aims at providing an efficient tool for classifying important damage scenarios. In contrast to local approaches, where damage scenarios in different locations are identified using a sensor array, the present method requires only signals from a single vibration sensor.

First, time series temporal correlations are estimated for constructing initial damage sensitive feature (DSF) vectors. Second, to further reduce unmeasurable and uncontrollable effects from varying excitation characteristics and measurement noise, initial DSFs are transformed with the help of principal component analysis (PCA). Then, PCA scores from selected reference damage states are used to identify optimal subsets of principal components that maximize the classification accuracy for the training datasets. SDC is done with the help of a statistical classification approach based on Bayes' theorem. However, instead of being able to classify only single DSF samples, the application of an advanced test for statistical classification enables to use bins of DSF samples. This allows further improving the overall SDC accuracy. Additionally, performance properties of an SHM system can be precisely selected for a certain application. Finally, in the online operational phase, only straightforward calculations are performed for SDC in order to infer the present damage scenario after damage has been detected with one of the well-known approaches, such as statistical hypothesis testing.

The method is applied to a small scale WTB made of a glass-fiber reinforced epoxy composite material. Physical experiments are performed in the laboratory, where the WTB is excited with a fan generating a wind-like air stream, and damage scenarios are introduced non-destructively by attaching small masses. Insights form this work will pave the way for future developments of effective vibration-based SHM systems to facilitate improved safety and reliability of WTs at lower costs.

10171-13, Session 3

Using phase-based motion estimation technique to extract operating modal data for a wind turbine blade

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Image sensing techniques are being applied for structural dynamics identification, characterization, and health monitoring more often in the recent years. Although as a non-contact and full-field measurement method, image sensing and processing approaches have a long path to outperform the commercial sensing instruments (such as accelerometers, strain gages and laser vibrometer). The image processing based sensing approach are developing rapidly and gaining enormous attention in multiple engineering domain, including structural dynamics and modal analysis. Among numerous motion estimation and extraction practices, phase-based motion estimation may be considered as one of the most efficient techniques in terms of computation consumption and noise robustness. In this paper, phase-based motion estimation technique is employed for structural dynamics characterization of a 2.3-meter long Skystream wind turbine blade, and extracting its modal parameters (natural frequencies, mode shapes, and damping coefficients). Dynamic characteristic of wind turbine blade is an important part of blade design and manufacturing, and phase-based motion estimation can provide reliable full-field planar motion information for manufacturing certification or model updating. Furthermore, the results obtained from phase-based motion estimation have a good correlation with the modal parameters extracted from conventional accelerometer measurements and also the updated FEM model. The first three bending mode shapes and the first edgewise mode shape are successfully validated, which have significant importance in blade design.

10171-14, Session 3

Scheduling monitoring for optimizing life-cycle costs and reliability of wind turbines

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Optimization of the life-cycle costs and reliability of offshore wind turbines (WTs) is an area of immense interest due to the widespread increase in wind power generation across the world. Though there has been significant research done in this field for structures such as bridges and offshore oil and gas platforms, less research has been conducted for the costs and reliability optimization of offshore WTs. Most of the existing studies have used structural reliability and the Bayesian pre-posterior analysis for optimization. This paper proposes an extension of the previous approaches as a novel framework for multi-objective probabilistic optimization of the total life-cycle costs and reliability of WTs by combining the elements of structural reliability analysis (SRA), Bayesian pre-posterior analysis with neuro-fuzzy computing such as Adaptive Network-Based Fuzzy Inference System (ANFIS) and optimization through a genetic algorithm (GA). The SRA techniques are adopted to compute the probabilities of failure and damage occurrence associated with the deterioration model. The probabilities are used in the decision tree and are updated using the Bayesian analysis. The decisions regarding the monitoring and inspection schedules are visualised through decision trees and the objective functions for cost and reliability are formulated, followed by multi-objective optimization of the objective functions. The joint ANFIS-GA optimization approach has not been explored for optimization of optimal monitoring and inspection schedules in the existing literature. ANFIS is a hybrid intelligent system that combines the aspects of neural networks and fuzzy logic rules and learns from the input and output datasets presented to the system. The output of this framework would determine the optimal structural health monitoring and maintenance schedules to be imolemented during the life span of offshore WTs while maintaining a trade-off between the life-cycle costs and reliability of the structures. Numerical illustrations with fatigue as the main mode of structural deterioration will be demonstrated.

10171-15, Session 3

Multi-objective optimization for predictive control applied to large scale wind turbines

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Manufacturing and maintenance costs have been a rising problem of large scale wind turbines. Model predictive control (MPC) is a promising approach to deal with multivariate conflicting objectives using weights tuning approach. In this research, an enhanced multi-objective optimization for predictive control is applied to find an optimal solution between multivariate objectives, such as, the energy capture, loads on multivariate turbine components and pitch actuator usage, with Pareto surface. The proposed algorithm is tested in the nonlinear NREL offshore 5-MW baseline wind turbine. The application of this strategy achieves enhanced balance of component loads and power capture in Region 3 compared with a baseline gain scheduling PID collective controller.

10171-9, Session PMon

Nanocomposite functional paint sensor for infrared detecting and energy harvesting

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This article reports the functionality of Paint-PLZT composite films for use in pyroelectric infrared sensors and energy conversion devices. Smart Paint-Lead Lanthanum Zirconate Titanate (Paint-PLZT) nanocomposite films have been fabricated by the conventional paint-brushing technique on copper substrate. The pyroelectric and dielectric properties of the composite films were measured for their use in uncooled infrared detectors and thermal energy conversion devices. The properties investigated include: dielectric constants (ε' and ε'') ; pyroelectric coefficient (p); and conductivity as a function of temperature. From the foregoing parameters, material's figure-of-merits, for infrared detection and thermal energy conversion, were calculated. The results indicated that composite films are functional and figure-of-merits increase with increase in amount of PLZT nanoparticles in paint. Based on the preliminary results obtained, Paint-PLZT films are attractive for use in un-cooled thermal sensing elements and thermal energy conversion devices, especially in applications where flexible and curved-surface sensors are required. Efforts are being made to investigate the sensitivity of nanocomposite films on copper substrate to mechanical vibrations. Thus, could be utilized for energy scavenging combining piezoelectric and pyroelectric effects. Work supported through NSF-RISE grant (HRD 1546965).

10171-26, Session PMon

Building environment assessment and energy consumption estimation using smart phones

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Most of traditional energy consumption monitoring technologies have a high cost of equipment, inconvenient mobile, less data acquisition and other shortcomings, so they can not be applied to all buildings. Therefore, we hope to develop a mobile phone application to collect and process the environmental information such as temperature, humidity and illumination, thus achieving the monitoring of energy consumption. This technology makes full use of the advantages of the mobility of smart mobile clients, and establish a network of energy monitoring system. With the advantages of large sample size and low cost, the technology is expected to make important contribution in the future environmental management, energy conservation and emission reduction.

Building energy consumption, including heat consumption and power consumption, can be estimated by the APP, which can evaluate the thermal comfort of environment.

The total energy consumption of heating Q is made up of fundamental heat consumption of building envelope Q1, additional heat consumption of building envelope Q2 and infiltration heat consumption Q3. Fundamental heat consumption of building envelope Q1 is related to the area and thermal conductivity of outer wall, outer window as well as roof. Additional heat consumption of building envelope Q2 is mainly related to orientation correction ε1, wind rate ε2 and high attachment rate ε3. Infiltration heat consumption Q3 is mainly related to osmotic cold air volume and temperature.

The user can choose from the two kinds of power consumption calculation, the electricity project and the valuation cycle electricity project. In the former, daily average power consumption Pd is equal to the monthly electricity consumption Pm which the users' fill-in are divided by 30. In the latter, Pd is equal to the electricity consumption of the valuation cycle divided by computation period.

Investigation of thermal comfort functions are implemented in the software. According to the user's selection, thermal sensation vote (TSV), thermal comfort vote (TCV) and heat can accept the vote distribution and the average results, specific problem setting and tested corresponding parameters, which can roughly reflect the user's thermal comfort, the feedback to related departments to make proper adjustments, for example, users vote bias uncomfortable partial heat, existing heating overheat waste in winter.

The function design of this APP contains four main parts: weather module, energy consumption module, building indoor environment module and thermal comfort evaluation module.

In weather module, by invoking the data of GPS sensor, this application could get the weather information such as relative humidity, wind direction, wind force and so forth every two hours from the meteorological station, thus realizing the weather forecasting function. In energy consumption module, after putting room parameters of aspect, area of the exterior wall and so forth, the application will compute four indicators respectively: the fundamental heat consumption of building envelope Q1, the additional heat consumption of building envelope Q2, the infiltration heat consumption Q3 and the total energy consumption of heating Q.

Similarly, the daily or monthly average electricity consumption can be computed according to users' inputting. In building indoor environment module, by invoking the built-in sensors of modern smart phones, the application can measure the internal thermal and humid environment, luminous environment and acoustic environment of the building directly. Besides, this APP can show the indoor temperature and relative humidity, the illumination of the working plane, environmental noise level and the percentage deviation according to the standard. However, temperature and humidity measurement temporarily supports the smart phones with the environmental temperature and humidity sensors only, such as Samsung S4, Note3 and MI 2/2s/3. The thermal comfort evaluation function of the application requires to collect the data of two mainly aspects: one is the personal information related to thermal comfort such as gender and age; the other is thermal sensation vote, thermal comfort vote and thermal acceptability vote, which are all put in by users. With collection and transmission, a thermal comfort fundamental database of an actual structural internal environment can be built up.

Android smart phone's built-in sensors are called to directly measure various environmental data, and the acquired data is transferred to the premade built server. After screening, operation, data analysis and results statistics, the regional differences in building energy consumption will be obtained. And each time users access to data, no matter it is a sensor acquisition or operation, the information that including Android ID, monitoring time, GPS, building information, input and output data and so forth will be automatically uploaded to the corresponding categories of the database. The database has a variety of retrieval functions to facilitate and export data according to categories. At the same time, the data can be filtered, merged, and so on. The information such as the result of thermal comfort evaluation, power consumption and heat consumption is also intuitively presented at the corresponding position on the map of website home page (http://www.energydb.net/).

By using of big data and cloud technology, a mobile phone application based on Android system is developed. By collecting and calculating the environmental variables such as temperature and humidity, the construction environment evaluation and energy consumption estimation are completed. After the statistics of the data uploaded, regional difference can be obtained, thus providing a more accurate basis for macro-control and research of energy, haze, greenhouse effect.

10171-27, Session PMon

Local elasticity mapping of aluminum matrix composites using scanning acoustic microscopy

Theodoti Kordatou, Ilias K. Tragazikis, Theodoros E. Matikas, Univ. of Ioannina (Greece)

Scanning acoustic microscopy is based on the difference in propagation time between the direct reflection and the Rayleigh wave. This study deals with the development of a fully automated acoustic microscopy method in order to determine the near-surface elastic properties and map the surface and sub-surface features in metallic and composite materials. This method allows the detection and analysis of Rayleigh waves, which are sensitive to subtle changes in the material's elastic properties. Via this process the periodicity of the V(Z) curve can be initially assessed with the aim to determine the local Rayleigh velocity of the material. An advantage of the method is that the user's input is only needed in the initial setup phase. In this work, the automated acoustic microscopy method was applied for the assessment of aluminum and Al-SiC metal matrix composites.

10171-28, Session PMon

Cement-based materials with graphene nanophase

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Cement matrix composites with a conductive phase, which acts as nano-reinforcement, lead to the development of innovative products. A matrix with carbon based nano-inclusions (graphene, carbon nanotubes, carbon nanofibers, carbon black) obtains multi-functional properties like enhanced mechanical, electrical, elastic and thermal properties and, therefore, the advantage of self-sensing in case of an inner defect. This research aims to characterize the nano-modified cement mortars with different amount of graphene nanophase. The results will be compared with data obtained from nano-materials containing multi-walled carbon nanotubes. Comprehensive characteristics of these cement-based nanocomposites have been determined using destructive and nondestructive laboratory techniques. Flexural and compressive strength, as well as the fracture toughness were measured. During four point bending tests, acoustic emission monitoring allowed for real-time identification of the damage process in the material. In order to determine the fracture energy, single-edge notch specimens were used. The estimation of the ultrasonic velocity in nanocomposites with different amounts of nano-inclusions led to the determination of their elastic properties. The electrical surface resistivity was measured by applying a known D.C. voltage using a contact testing method.

10171-29, Session PMon

Energy harvesting from polyvinylidene fluoride (PVDF) modified by nanoparticles

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Polyvinylidene Fluoride (PVDF) films were modified by ZnO nanoparticles to form nanoporous structures, thus enhanced the piezoelectric effect due to the fact the films yielded considerably large deformation under a small force. To fabricate the films, PVDF solution and Zinc Oxide (ZnO) nanoparticles were mixed uniformly and then casted on a flat glass surface, followed by etching ZnO away. ZnO nanoparticles worked as templates to create pores in PVDF so that high flexibility was achieved. In this study, such films were bonded to a cantilever beam to harvest energy from mechanical vibration. The modified PVDF film was first poled by applying an electric field of 60 MV/m across the thickness of the films for 2 h. Subsequently, the PVDF transducer was mounted on the cantilever beam made of glass fiber using a two-part epoxy resin and then placed in a conventional oven for 12 h at 30 oC. After curing, the cantilever beam was attached to a shaker and the transducer was connected to a bridge circuit that can charge a battery. The shaker was driven by a function generator to produce vibration with various frequencies and amplitudes. This energy harvesting setup was used to analyze the effectiveness of the PVDF transducer by monitoring charging rates of the battery. Two sets of ZnO nanoparticles with different sizes, one is 35-45 nm in diameter and the other 10-25 nm, were used for making the PVDF films and thus inducing different porosities. Therefore, the effect of the porosity on energy harvesting was also investigated.

10171-500, Session Plen

NDE for the 21st century: industry 4.0 requires NDE 4.0

Norbert G. Meyendorf, Iowa State Univ. (United States)

Industry 4.0 stands for the fourth industrial revolution that is ongoing at present. Industry 4.0 is a terminology preferred used in Europe to characterize the integration of production and communication technologies, the so called "smart factory". The first industrial revolution was the mechanization of work. The second was mass production and the assembly line. While the third revolution was the computer integrated manufacturing. Industry 4.0 encompasses the complete networking of all industrial areas. Lowering costs and efficient in-time production will be possible also for low numbers of very unique parts for example by additive manufacturing (3D

printing). A significant aspect is also quality and maintainability of these sometimes unique structures and components. NDE has to follow these trends, not only by adapting NDE techniques to the new technologies, but also introducing the capability of cyber systems into the inspection and maintenance processes. The requirements and challenges for this new technological area will be discussed. Chances for applications of new technologies and systems for NDE will be demonstrated online.

10171-17, Session 4

Time-frequency analysis of guided ultrasonic waves used for assessing integrity of rock bolts

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Rock bolts are commonly used to reinforce the roof and the walls of tunnels or mines in order to increase staff security as well as to minimize the risk of interference during the work. Rock bolts are steel bars of different types that are grouted and often anchored in deep boreholes in the rock mass using a grout (cement or epoxy). Long-range guided ultrasonic waves can be applied to investigate rock bolts' status, especially, their grouting condition.

The purpose of this paper is to demonstrate application of the time-frequency analysis (TFA) for processing guided ultrasonic waves measured by means of a specially designed Swedish ultrasonic rock bolt tester (RBT) during inspection of rock bolts grouted in a rock mass. A pulse-echo method is adopted in the RBT instrument, as the most appropriate for the in-field applications. The instrument features an application tailored ultrasound probe with transmitter excited by a low frequency (below 100kHz) pulse train signal, which generates high-energy guided waves. Its receiver is capable of receiving weak echoes reflected from the discontinuities at the bolt surface as well as its end-echo, which have propagated back and forth in the range of up to 4 meters.

This paper includes a short review of the time-frequency techniques and presents methods for analysis of the measured guided ultrasonic waves using the TFA. The proposed TFA methodology is first demonstrated on simulated signals and then verified using experimental signals gathered from the prepared rock bolts instrumented with artificial defects simulating grout discontinuities and grouted in a granite rock.

10171-18, Session 4

Effective source location of damages in cylindrical high pressure composite vessels through advanced zonal location method

Dong-Jin Yoon, Byeong-Hee Han, Choon-Su Park, Il-Bum Kwon, Korea Research Institute of Standards and Science (Korea, Republic of)

Usually CFRP composites combustion chamber for high performance propulsion engine are using under the condition of high temperature or high pressure. These kinds of composites cylindrical structures are very vulnerable to the external impact damages, and also this damage gives an effect to the changes of products performance. So, we need an early detection of damages in this structure in order to avoid a catastrophic failure. Sometimes they have a need for inspection of damage existence and their location after long time keeping of vessels when it goes to use. In this case, we have to measure the status of the vessel at the field condition or have to do in-situ monitoring for early detection of damages. Especially, acoustic emission technique compared to other nondestructive testing technology is one of the most powerful techniques being able to detect damages and to identify damage location. In this study, in order to assess more simply the existence and location of damages by external impact in the high pressure cylindrical composite structures, we have used a new source location algorithm. That is, an advanced zonal location method has been proposed by using acoustic emission parametric technique with location coordinates algorithm. And also an experimental verification was conducted by using the new proposed technique in the multi-layered composite cylindrical structures. From experimental results, the new proposed damage assessment algorithm is verified for assessing very effectively the unexpected external impact damages in these kinds of cylindrical composite structure.

10171-32, Session 4

Condition monitoring of rotor blades and foundations of wind turbines

Bernd Frankenstein, Fraunhofer IKTS-MD (Germany); Norbert G. Meyendorf, Iowa State Univ. (United States); Bianca Weihnacht, Tobias Gaul, Lars Schubert, Eberhard Schulze, Fraunhofer IKTS-MD (Germany)

No Abstract Available

10171-19, Session 5

Analytical modeling and data acquisition software development for rotor dynamics testing in spin laboratory

Ali Abdul-Aziz, Kent State Univ. (United States); Mark R. Woike, NASA Glenn Research Ctr. (United States); Daniel Arble, Univ. of Maryland, College Park (United States)

Gas turbine engine components undergo high rotational loading another complex environmental conditions. Such operating environment leads these components to experience damages and cracks that can cause catastrophic failure during flights. There are traditional crack detections and health monitoring methodologies currently being used which rely on periodic routine maintenances, nondestructive inspections which often time involves engine and components dis-assemblies. Furthermore, these methods do not offer adequate information about the faults, especially, if these faults at subsurface or not clearly evident. At NASA Glenn research center, the rotor dynamics laboratory is presently involved in developing newer techniques that are highly dependent on sensor technology to allow health monitoring and prediction of damage and cracks in rotor disks. These approaches are noninvasive and relatively economical. Spin tests are being performed using a subscale test article mimicking turbine rotor disk undergoing rotational load. Non-contact sensors such as capacitive and microwave are used to measure the blade tip displacement in an attempt develop a model to help assess/predict the faults in the rotor disk. Data collection is a major component in this process, it covers both combined experimental and analytical procedure and as a result, an upgraded version of the data acquisition software which is based on LabVIEW program has been implemented to help efficiently run tests and analyze the results. Results obtained from the test data and related analytical model including the leading and key features of the updated software are being presented and discussed.

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10171-20, Session 5

Wave path calculation of total focusing method for phased array imaging to evaluate weld zone of elbow pipes

Choon-Su Park, SeungHyun Cho, Wonjae Choi, Korea Research Institute of Standards and Science (Korea, Republic of)

It has long been non-destructively evaluated on weld joints of various pipes which are indispensable to most of industrial structures. Ultrasound evaluation has been used to detect flaws in welding joints, but some technical deficiencies still remain. Especially, ultrasound imaging on weld of elbow pipes has many challenging issues due to varying surface along circumferential direction. Conventional ultrasound imaging has particularly focused on ultrasonic wave propagation based on ray theory. This confines the incident angle and the position of an array transducer as well. Total focusing method (TFM), however, can provide not only high resolution images but also flexibility that enables to use ultrasonic waves to every direction that they can reach. This leads us to develop a method to get images of weld zone from an elbow part that curves. It is inevitable of each ultrasonic wave from the array transducer to transmit through different media and to be reflected from the boundary with angles along the curved surface. To form a correct PA image, careful calculation is made to ensure that time delay of receive-after-transmit is correctly shifted and summed even under non-planar boundary condition. Here, a method to calculate wave paths for the zone of interest at weld joint of an elbow pipe is presented. Numerical simulations of wave propagation on an elbow pipe are made to verify the proposed method. It is also experimentally demonstrated that the proposed method is well applied to various actual pipes that contains artificial flaws with a flexible wedge.

10171-21, Session 5

Non-invasive imaging tools for SMAs inspection

Nicolas P. Avdelidis, Hai Zhang, Univ. Laval (Canada); Dimitrios A. Exarchos, Univ. of Ioannina (Greece); Clemente Ibarra-Castanedo, Xavier P. V. Maldague, Univ. Laval (Canada); Theodoros E. Matikas, Univ. of Ioannina (Greece)

Shape Memory Alloys (SMAs) are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli. They can sense temperatures or stress as a function of change in damping, stiffness, electrical resistivity and deflection. It is specifically the latter aspect that makes SMAs highly interesting for particular applications, such as improving the integrity of structures before or during their in-service life, since it is the actuation function built into the material. Non invasive imaging tools such as infrared thermography (IRT) and terahertz (THz) imaging are techniques that could find use for surface inspection, quality control of applied coating and detection, location and characterization of any potential deformation of the SMAs. In this work, these two advanced imaging tools were used to inspect and to detect any structural imperfections (defects, cracks etc.) on different SMA samples. The presented imaging tools could provide one of the best capabilities for in service inspection in the future, for large metallic structures involving SMAs (i.e. aerospace, automotive, robotics, etc).

10171-22, Session 5

Experimental investigation of wave dispersion in hardened concrete and reference liquid media

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Nowadays, more and more, the monitoring of concrete's setting and hardening as well as concrete's condition assessment and mechanical characterization is realized with the Ultrasonic Pulse Velocity technique. However, despite its increasing use, the high potential and the vast applicability over a wide range of materials and structures, the aforementioned nondestructive testing technique is only partially exploited since a) a default pulse is transmitted b) a single frequency dependent on the testing equipment (pulse generator and sensors) is excited and c) the first part of the signal is only considered. Moreover, the technique, as defined by its name, is based on pulse velocity measurements which strongly rely on a predefined threshold value for the calculation of the travel time between the transmitting and receiving sensor. To overcome all these issues, in the current experimental campaign, user-defined signals are generated, a broad range of ultrasonic frequencies is excited, while the full length of the signal is also taken into account. In addition, the pulse velocity measurements are replaced by the more advanced phase velocity calculations determined by reference phase points of the time domain signals or by phase differences of the signals transformed in the frequency domain. The experiments are conducted in both fresh and hardened concrete specimens but the aggregates are substituted by spherical glass beads of different sizes and contents in order to better control the microstructure. The results in both cases show dispersive trends with opposite sign implying that setting time can alternatively be defined from the sign change.

10171-23, Session 5

Novel dynamic thermal characterization of multifunctional concretes with phase change materials

Anna Laura Pisello, Claudia Fabiani, Antonella D'Alessandro, Filippo Ubertini, Univ. degli Studi di Perugia (Italy); Luisa Fernanda Cabeza, Univ. de Lleida (South Sudan); Franco Cotana, Univ. degli Studi di Perugia (Italy)

Concrete is widely applied in the construction sector for its reliable mechanical performance, its easiness of use and low costs. It also appears promising for enhancing the thermal-energy behavior of buildings thanks to its capability to be doped with multifunctional fillers. In fact, key studies acknowledged the benefits of thermally insulated concretes for applications in ceilings and walls. At the same time, thermal capacity also represents a key property to be optimized, especially for lightweight constructions. In this view, Thermal-Energy Storage (TES) systems are recently integrated into building envelopes for increasing thermal inertia. More in detail, the numerical and experimental investigation showed how the inclusion of Phase Change materials (PCMs), as an acknowledged passive TES strategy, can be effectively included in building envelope, with promising results in terms of thermal buffer potentiality. In particular, this work builds upon previous papers aimed at developing the new PCM-filled concretes for structural applications and optimized thermal-energy efficiency, and it is

focused on the development of a new experimental method for testing such composite materials in thermal-energy dynamic conditions simulated in laboratory. The key findings show how the new composites are able to increasingly delay the thermal wave with increasing the PCM concentration and how the thermal conductivity varies during the course of the phase change, in both melting and solidification processes. The new analysis produces useful findings in proposing an effective method for testing composite materials with adaptive thermal performance, much needed by the scientific community willing to study building envelopes dynamics.

10171-24, Session 5

Crash response of a new 3D open cell structure for sandwich cores

Luca Boccarusso, Univ. degli Studi di Napoli Federico II (Italy); Fulvio Pinto, Univ. of Bath (United Kingdom); Antonio Langella, Univ. degli Studi di Napoli Federico II (Italy); Michele Meo, Univ. of Bath (United Kingdom)

Sandwich panels are strongly dependent on the properties of the core for dissipating energy during an impact event. In particular, open cell structures can be employed to improve the properties in the out of plane direction and reduce the weight of components for aerospace and aircraft industries. This work is focused on the design and manufacturing of a new 3D open cell structure for sandwich core applications based on a new typology of lattice structure for lightweight components with high impact performance. The unit cell of the proposed lattice structure was opportunely designed in order to have an arc geometry in each 3D space directions and take advantages of all the benefits connected to the use of this shape. In order to conduct a preliminary study on the mechanical properties of the structure, samples were manufactured using Acrylonitrile-butadiene-styrene (ABS) by using a conventional 3D printer. The built unit cell structure is characterised by a relative density of 0.26 with a dimension of 22 x 20 mm. Crash impact tests at 22 and 40 J were carried out and the experimental results were compared to numerical simulations obtained using LS-Dyna as Finite Element (FE) software. Results showed that the structure did not show a catastrophic failure until 40 J thank to the damping arc behaviour that is able to elastically dissipate impact energy. The results of the FE analyses in terms of time-displacement behaviour were in good agreement with the experimental data.

10171-25, Session 5

Detection and characterization of exercise induced muscle damage via thermography and image processing

Nicolas P. Avdelidis, Univ. Laval (Canada); Vassilios Kappatos, Univ. of Southern Denmark (Denmark); George Georgoulas, Luleå Univ. of Technology (Sweden); Petros Karvelis, Technological Educational Institute of Epirus (Greece); Chara K. Deli, Univ. of Thessaly (Greece); Panagiotis Theodorakeas, Maria Koui, National Technical Univ. of Athens (Greece); Athanasios Z. Jamurtas, Univ. of Thessaly (Greece)

Exercise induced muscle damage (EIMD), is usually experienced in humans who have been physically inactive for prolonged periods of time and then begin with sudden training trials and in athletes who train over their normal limits. EIMD is not so easy to be detected and quantified, by means of commonly measurement tools and methods. Thermography has been used successfully as a research detection tool in medicine for the last 6 decades but very limited work has been reported on EIMD. The main purpose of this research is to assess and characterize EIMD, using Thermography and Image Processing techniques.

Extensive experimental investigation was carried out, acquiring thermographic images of the rectus femoris muscle before, immediately post and 24, 48 and 72 hours after an acute bout of eccentric exercise (5 sets of 15 maximum repetitions), on males and females (20-30 year old). Eccentric exercise was performed with the one lower extremity, whereas the other lower extremity served as control. Image processing algorithms are comprised by different sections for automatic quality improvement of the acquiring thermography images and automatically calculate the number of EIMD areas, measuring their area and coordinate them. The results showed that DOMS and creatine kinase increased significantly 24 hours and remained elevated up to 72 hours post-exercise. Torque decreased significantly 24 hours and remained elevated up to 72 hours post-exercise. Changes in Temperature were also recorded post exercise. Correlation between the image processing analysis and the physically measures quantities was achieved.

10171-31, Session 5

Briquetting and carbonization of biomass products for the sustainable productions of activated carbons

Nasrin B. Khorasgani, Bahareh Karimibavani, Mohammed Alamir, Amy P. McClain, Ramazan Asmatulu, Wichita State Univ. (United States)

One of the most environmental concerns is the climate change because of the greenhouse gasses, such as CO_2, N_2O, CH_4, and fluorinated gases. The big majority of CO_2 is coming from burning of fossil fuels to generate steam, heat and power. In order to address some of the major environmental concerns of fossil fuels, a number of different alternatives for renewable energy sources have been considered, including sunlight, wind, rain, tides and geothermal heat and biomass. In the present study, two different biomass products (three leaves and grasses) were collected from the local sources, cleaned, chopped, and mixed with corn starch as a binder prior to the briquetting process at different external loads in a metallic mold. A number of tests, including drop, ignition and mechanical compression were conducted on the prepared briquettes before and after stabilizations and carbonization processes at different conditions. The test results indicated that briquetting pressure and carbonizations are the primary factors to produce stable and durable briquettes for various industrial applications. Undergraduate students have been involved in every step of the project and observed all the details of the process during the laboratory studies, as well as data collection, analysis and presentation. This study will be useful for the future trainings of the undergraduate engineering students on the renewable energy and related technologies.

10172-21, Session PMon

A study on the accordion structure type thermoelectric power generation module using the metal direct bonding technology

Hiroshi Sato, So Baba, National Institute of Advanced Industrial Science and Technology (Japan); Tetsuro Yanaseko, Kogakuin Univ. (Japan); Hiroshi Asanuma, Chiba Univ. (Japan)

The thermoelectric power generation device can take out electric energy from thermal energy directly. In order to transform a difference of temperature into electric power efficiently, it is common to make the thermoelement of N-type and P-type into pi structure. Since the thermoelectric power of an element was small, much pi structures needed to be connected with series, but when a large number were connected with series, there was a problem that internal resistance will become large.

In this paper, to solve these problems, we have proposed an inexpensive nickel plate and stacked ϖ-type thermoelectric devices the aluminum plate was bonded directly. The insulating layer by sandwiching a nickel plate and the aluminum plates were bonded to the N-type element while maintaining the ϖ structure (Ni) and P-type element (Al) directly. Seebeck also a material having a low effect, showed that by suppressing the rise of the internal resistance even if a large number stacked produce a large number of ϖ-type structure at a time, it is possible to power generation. Also, when using the anodic oxide film was produced on the aluminum surface as an insulating layer, an insulating layer portion has been found that not bonded to the nickel.We utilize this characteristic positively, by peeling off the insulating layer portion, was developed an accordion-type thermoelectric device that can make a temperature difference increases the more cooling effect. This structure also flexible combines, it is possible to cope with the shape of a variety of heat sources.

10172-22, Session PMon

Bimolecular material systems

Donald J. Leo, The Univ. of Georgia (United States)

Nature uses stimuli-responsive biomolecules to control the transport of charge and mass at the nanoscale. These biomolecules are embedded in cells, which in turn are the building blocks for complex biological systems that exhibit emergent behavior. This talk will discuss our recent work in mimicking the hierarchical nature of biological materials and material systems through the use of reconstituted stimuli-responsive channels embedded into synthetic materials. Based on the concept of a droplet-interface bilayer, we have created a “biomolecular unit cell” that consists of a liquid or hydrophilic gel encased in a hydrophobic matrix. Lipid monolayers are incorporated at the hydrophilic-hydrophobic interface, and physical contact between two compartments results in the creation of a lipid bilayer. This lipid bilayer mimics the functional properties of cells and enables the incorporation of stimuli-responsive biomolecules such as voltage-gated pores, mechanosensitive channels, and light-activited molecules. In the past two years we have successfully created networks of these materials and, working with other researchers, demonstrated that we can create material systems that exhibit collective behavior. Unit cells have been used as building blocks to create fluid flow sensors, air flow sensors, and recent results have demonstrated the ability to encase hundreds of unit cells into solid materials.

10172-500, Session Plen

A smart structural dynamics strategy for testing tomorrow’s structures

David J. Ewins, Imperial College London (United Kingdom)

All structures for which dynamic behaviour is a primary consideration require application of advanced methods of both theoretical and experimental structural dynamics. Specifically, advances in predictive methods of simulation (especially in the numerical analysis aspects) can demand matching advances in testing to provide commensurate accuracy and coverage of the validation of their output. Acquisition of an improved prediction capability is usually accompanied by an increase in expectations and demands for greater reliability in the predicted behaviour. As a direct result, progress in testing and simulation must advance in step and improvements in testing can often be achieved by smarter implementation of contemporary test procedures based on interpretation of the more advanced models used for their design. This lecture presents an integrated test-analysis strategy for ensuring that next-generation structures of all types exhibit much improved reliability in their structural performance.

10172-1, Session 1

Some recently obtained results in classical vibration and acoustics: coexistence of traveling and standing waves in a one-dimensional non-dispersive continuum *(Invited Paper)*

Larry A. Bergman, Univ. of Illinois at Urbana-Champaign (United States)

Dan Inman’s contributions to classical vibration and structural dynamics are well known, particularly to those participating in this symposium celebrating Dan’s long and productive academic career. His earliest work, published in the 1980s, focused on stability and performance of nonconservative linear systems, as well as the modeling of various damping mechanisms. Likely not well known is that Dan and I, in conjunction with Tom Banks and one of his postdocs, coauthored a paper in the Journal of Applied Mechanics in 19983, in which we proved the existence of normal modes in damped discrete-continuous systems, the product of a long weekend of analysis and beer while voluntarily sequestered in a Holiday Inn in Raleigh, NC. Much of the work leading to that paper was the result of my collaboration and series of papers on combined and constrained linear systems with the late Jim Nicholson, from 1984 to 1989, and subsequently with a number of my graduate students, most notably Michael McFarland and Gerhard Lueschen during the early 1990s. This led to some further work with Alexander Pesterev, Chin An Tan and Ben Yang addressing the dynamics of continua carrying moving loads and subsystems. At that point, it seemed like a good time to move on to other research problems. However, some years later I was perusing the first chapter of the excellent book on vibrations and waves by Peter Hagedorn and Anirvan DasGupta4 in which the free vibration of a linear axial bar, fixed at one end and connected to ground at the other end through a linear viscous damper is addressed. It is shown there that, for a fixed set of bar parameters and the special case of the damping coefficient equal to /EAc (c being the speed of sound in the continuum), no eigenvalues exist. Thus, energy imparted to the bar via harmonic motion of the fixed support will propagate through the bar and be fully dissipated in the damper, in effect making the bar appear to be semi-infinite. I will show some recent results by members of our group (Antoine Blanchard, Ethan Xiao, Alex Vakakis, Michael McFarland, Larry Bergman), in which this phenomenon has been exploited in several other non-dispersive media, the taut string and the circular acoustic duct, incorporating viscoelastic supports or absorbers to produce responses to external excitation that exhibit complete separation of traveling and standing waves, in effect localizing the vibration over a portion of the domain.

1 Dedicated to Professor Daniel J. Inman on the occasion of his 70th birthday.

2 Research Professor and Professor Emeritus

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10172-2, Session 1

Fractional order absolute vibration suppression (AVS) controllers

Yoram Halevi, Technion-Israel Institute of Technology (Israel)

Absolute vibration suppression (AVS) is a control method for flexible structures. The first step is an accurate, infinite dimension, transfer function (TF), from actuation to measurement. This leads to the collocated, rate feedback AVS controller that in some cases completely eliminates the vibration. In case of the 1D wave equation, the TF consists of pure time delays and low order rational terms, and the AVS controller is rational. In all other cases, the TF and consequently the controller are fractional order in both the delays and the "rational parts". The paper considers stability, performance and actual implementation in such cases.

10172-3, Session 1

Multifunctional smart composites with integrated carbon nanotube yarn and sheet

Devika Chauhan, Guangfeng Hou, Vianessa Ng, Sumeet Chaudhary, Michael Paine, Nicholas Lalley, Massoud Rabiee, Marc M. Cahay, Vesselin N. Shanov, David B. Mast, Univ. of Cincinnati (United States); David S. Lashmore, The Univ. of New Hampshire (United States); Yijun Liu, Univ. of Cincinnati (United States); Sergey Yarmolenko, Svitlana Fialkova, North Carolina A&T State Univ. (United States); Zhangzhang Yin, Mark J. Schulz, Univ. of Cincinnati (United States)

Multifunctional smart composites (MSCs) describe materials that combine; the electrical and thermal conductivity, high tensile and shear strength, good impact toughness, and high stiffness properties of metals; the light weight and corrosion resistance properties of composites; and the sensing or actuation properties of smart materials. Present laminated carbon and glass fiber polymeric composite materials have high tensile strength and are light in weight, but they lack good electrical and thermal conductivity and they are sensitive to delamination. Carbon nanotube yarn and sheets are lightweight, electrically and thermally conductive materials that can be integrated into laminated composite materials to form MSCs. This paper describes; (1) the continuous manufacturing of very high quality carbon nanotube yarn and sheet used to form MSCs, and (2) Integrating the nanotube yarn and sheet into composites at low volume fractions. Various up and coming technical applications of MSCs are discussed including; (1) composite toughening for impact and delamination resistance, (2) thermal transport, (3) electrical discharge of static electricity caused by lightning strike, (4) structural health monitoring, (5) electromagnetic shielding, (6) energy harvesting, and (7) structural power conduction. The global carbon nanotube overall market size is estimated to grow from $2 Billion in 2015 to $5 Billion by 2020 at a CAGR of 20%. Nanotube yarn and sheet products will encompass aircraft, wind machines, automobiles, electric machines, textiles, acoustic attenuators, light absorption, electrical wire, sporting equipment, tires, athletic apparel, thermoelectric devices, biomedical devices, lightweight transformers, and electromagnets.

10172-4, Session 2

Electromechanical impedance-based fault detection in a rotating machine by using an operating condition compensation approach

Karina M. Tsuruta, Diogo S. Rabelo, Aldemir Ap Cavalini Jr., Roberto M. Finzi, Valder Steffen Jr., Univ. Federal de Uberlândia (Brazil)

Condition-based maintenance (CBM) systems that use sensors network for damage detection in rotating machinery have constantly been evolving. Such approaches aim to detect the presence and severity of damage on a statistical basis. The aim of this paper relies on the correct detection of incipient faults in rotating shafts by using a real-time Impedance-based Structural Health Monitoring (ISHM) method, with a low-cost and portable device. This technique monitors changes in the electric impedance of piezoelectric transducers, acting simultaneously as actuators and sensors, which are bonded to the host structure. With the use of damage metrics, these changes can be quantified so that the presence and severity of damage can be detected. This is possible since the electrical impedance of the sensor is directly related to the mechanical impedance of the structure. However, the Frequency response functions (FRFs) resulting from this method are susceptible to environmental and operational conditions that must be accounted for in order to avoid false diagnostics. For this aim, in this contribution, an operating condition compensation technique is used to minimizes the effects of the temperature and dynamic load on the impedance signatures of the rotor system. The compensation technique is based on a hybrid optimization method associated with different damage metrics. Additionally, a statistical model is used for threshold determination based on the Statistical Process Control (SPC) method. Experimental results show that an incipient fatigue crack associated with bearing wear could be successfully detected with a probability of detection above 95 % confidence for the majority of sensors used.

10172-5, Session 2

Feedback control design based on spectral element method

Sanderson M. Conceição, Douglas D. Bueno, Vicente Lopes Jr., Univ. Estadual Paulista "Júlio de Mesquita Filho" (Brazil)

Frequency domain modeling has been developed to different engineering applications. In particular, the Spectral Element method (SEM) has been discussed in literature mainly for vibration control design and structural health monitoring once it allows to study unlimited range of frequencies. However, although different authors discuss classical control techniques like PID for SEM formulations there is a limited number of works involving modern control theory based on state space representation. In this context, this work introduces a new approach that allows to use feedback techniques in vibration control design based on SEM. The formulation is presented and numerical simulations are performed using the Timoshenko beam model with two PZT patch bonded. The PZT transducer effects are included too. Results show vibrations reductions of the first three modes of a campled-clamped beam and the proposed approach offers promise to control design using SEM.

10172-6, Session 2

Design and experimental verification of a semi-active pitch link for helicopter vibration attenuation

Marcel A. Clementino, Carlos De Marqui Jr., Univ. de São Paulo (Brazil)

Helicopters are inherently associated to noise and vibrations due to different phenomena related to fluid and structure interactions that usually occur in the main rotor blades. The induced vibrations are transmitted to the fuselage through the rotor hub and control commands (pitch link, for instance), and, therefore, may affect the comfort of pilots and passengers, limit the helicopter maximum forward speed, reduce the aircraft lifespan and increase maintenance costs. The fuselage vibration spectrum is dominated by some specific harmonic frequencies (N/rev), which depend on the number of blades (N) of the helicopter and. The Active Pitch Link presented in the literature is a mechanical system that incorporates a mechanism for helicopter blade pitch dynamic stiffness modulation at the root. The Active Pitch Link experimentally verified performance for helicopter rotor-induced vibration reduction was recently reported. Although a remarkable control performance has been achieved during whirl tower tests, the dependence on an external voltage source and possible mechanical failures (due to constant friction) are pointed out as drawbacks of the system. Therefore, this work reports on the design and experimental verification of a new semi-active pitch link system using piezoelectric material for vibration attenuation. Synchronized switching control techniques are employed to modify the stiffness or damping of the new pitch link and reduce vibration at a target frequency. Different experimental verifications are presented, including bench top vibration tests and whirl tower experimental tests. The new configuration proposed here refers to a solid-state electromechanical system that provides enhanced vibration attenuation.

10172-7, Session 2

Impedance-based structural health monitoring

Gyuhae Park, Chonnam National Univ. (Korea, Republic of); Daniel J. Inman Sr., Univ. of Michigan (United States)

This paper presents an overview of impedance-based structural health monitoring, which has been pioneered by Inman and his research group. The basic principle behind this technique is to apply high frequency structural excitations (typically greater than 30 kHz) through the surface-bonded piezoelectric transducers, and measure the impedance of structures by monitoring the current and voltage applied to the piezoelectric transducers. Changes in impedance indicate changes in the structure, which in turn can indicate that damage has occurred. For the last two decades, extensive research works have been performed to various applications, including mechanical, aerospace and civil structural components. The technique has been also extended to piezoelectric sensor diagnostics, concrete cure monitoring, and biomedical applications. This paper presents the summary of how this technique has been evolved with the significant contribution by Inman.

10172-8, Session 3

Dynamics of smart structures: from energy harvesting to metamaterials

Alper Erturk, Georgia Institute of Technology (United States)

This talk will review our recent efforts on the electroelastodynamics of smart structures for various applications ranging from nonlinear energy harvesting and acoustic power transfer to elastic wave guiding and vibration attenuation via metamaterials. The main focus will be placed on energy harvesting (theory and experiments) for small electronic components using piezoelectric transduction. The field of energy harvesting offers the promise of enabling self-powered electronic components for numerous applications ranging from conventional systems employing wireless sensor networks to next-generation components of the Internet of Things which will connect each individual to tens or hundreds of wireless devices for which periodic replacement or charging of

batteries will be either too costly or cumbersome. In the context of energy harvesting, we will discuss how to exploit nonlinear dynamic phenomena for frequency bandwidth enhancement as an alternative to narrowband linear-resonant devices. We will also cover inherent nonlinearities (ferroelastic nonlinearity and intrinsic/extrinsic nonlinear dissipation), and their interaction with intentionally designed nonlinearities, as well as electrical circuit nonlinearities. Our recent efforts on phononic crystal-enhanced elastic wave guiding and harvesting, low-frequency broadband vibration attenuation via locally resonant metamaterials, contactless acoustic power transfer, nonlinear vibration and bifurcation suppression using nonlinear circuits, and exploiting size effects via strain-gradient induced polarization (flexoelectricity) in centrosymmetric elastic dielectrics will also be summarized.

10172-9, Session 3

Integrated fiber optic structural health sensors for inflatable space habitats

Osgar John Ohanian III, Naman Garg, Matt Castellucci, Luna Innovations Inc. (United States)

Inflatable space habitats offer many advantages for future space missions; however, the long term integrity of these flexible structures is a major concern in harsh space environments. Structural health monitoring (SHM) of these structures is essential to ensure safe operation, provide early warnings of damage, and measure structural changes over long periods of time. To address this problem, the authors have integrated distributed fiber optic strain sensors to measure loading and to identify the occurrence and location of damage in the straps and webbing used in the structural restraint layer. The fiber optic sensors employed use the Rayleigh backscatter combined with optical frequency domain reflectometry algorithms to enable measurement of strain every 1.25 mm along the sensor. Mechanically coupling the fiber optic sensor to the flexible woven straps was a key challenge, and several methods were explored and are described here. The Kevlar woven straps that were tested exhibited large permanent deformation during initial cycling and continued to exhibit hysteresis thereafter, but the distributed strain sensors showed excellent linearity in measuring the strain in the straps. Damage was intentionally applied to a tensioned strap, and the distributed strain measurement clearly identified a distinct feature centered on the location of the damage. This change in structural health was identified at a loading that was less than half of the ultimate loading that caused a structural failure. This sensing technique will be used to enable integrated SHM sensors to detect loading and damage in future inflatable space habitat structures.

10172-10, Session 3

Piezoelectric energy harvesters for powering leadless pacemakers

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A miniature nonlinear piezoelectric energy harvester is designed to power state of the art leadless cardiac pacemakers from cardiac motions. The energy harvester (EH) converts myocardial motions to electricity to power leadless pacemakers. The device is composed of a bimorph piezoelectric beam confined in a gray iron frame. The system is assembled at high temperature and operated at the body temperature. The mismatch in the

coefficients of thermal expansion of the beam and the frame caused the beam to buckle in body temperature. This intentional buckling makes the beam unstable and improves the power production and robustness of the device. Having high natural frequency is a major problem in Microelectromechanical systems (MEMS) energy harvesters. Considering the small size of the EH, , the natural frequency is expected to be high. In our design, the natural frequency is lowered significantly by using a buckled beam and a proof mass. Since the beam is buckled, the design is bistable and nonlinear which increases the output power. In this paper, the natural frequencies and mode shapes of the EH are analytically derived. The terms corresponding to geometric nonlinearities are included in the electromechanical coupled governing equations. The simulations show that the device generates sufficient electricity to power leadless pacemakers.

10172-11, Session 3

Optical properties of NKN nanowire synthesized by controlled pulsed laser deposition

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Potassium sodium niobate, Na0.5K0.5NbO3 (NKN), single crystal nanowires were successfully synthesized using controlled pulsed laser deposition (PLD), and their optical properties were investigated. In the past decade great amount of emphasis has been put forward towards investigating different piezoelectric and ferroelectric materials as alternatives to widely used lead-based piezoelectric materials such as PbTiO3 (PZT) and Pb(Nb,Mg)- PbTiO3. [1] Among all the available alternatives to lead-based ferroelectric materials, NKN thin films, in particular, are considered most important due to their high Curie temperature, ferroelectric, piezoelectric and opto-electric properties. [2] In 2015 Kang et. al. [3] demonstrated the synthesis of NKN nanowires using PLD to produce vertically aligned single-crystalline nano-rod arrays on Nb:STO (100) substrate and investigated their piezoelectric properties.

In our approach, NKN nanowires were synthesized by altering the growth conditions specified by Kang et al. in order to successfully synthesize single crystal NKN nanowires on SrTiO3 substrate with a SrRnO3 base conductive layer. X-Ray Diffraction (XRD) scans were performed to confirm the single crystalline structure of the nanowires, Figure 1. Scanning Electron Microscope (SEM) imaging was used to confirm the presence of nanowires in the synthesized sample, Figure 2. The synthesized nanowires were 380–535 nm long with a diameter of 50 – 90 nm. UV-visible reflectance spectroscopy was used to study the optical properties and to determine the energy band gap of the synthesized NKN samples which, to our knowledge has not been previously reported for NKN nanowires.

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10172-12, Session 3

Recent developments on SMA actuators: understanding failure and fatigue

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Shape memory alloys (SMAs), due to their ability to repeatably recover substantial deformations under applied mechanical loading, have the potential to impact the aerospace, automotive, biomedical, and energy industries as weight and volume saving replacements for conventional actuators. While numerous applications of SMA actuators have been flight tested and can be found in industrial applications, these actuators are generally limited to non-critical components, are not widely implemented and frequently one-off designs, and are generally overdesigned due to a lack of understanding of the effect of the loading path on the fatigue life and the lack of an accurate method for predicting actuator lifetimes. In recent years, multiple research efforts have increased our understanding of fatigue and failure of SMAs. These advances, which will be reviewed in this talk, can be utilized to predict the fatigue lives and failure loads in SMA actuators. Additionally, these prediction methods can be implemented in order to intelligently design actuators in accordance with their fatigue and failure limits. In order to validate these prediction methods, both simple and complex actuator geometries and thermomechanical loading paths have been considered. Experimental data in this presentation is compared with FEA results and will consist of both actuation fatigue and actuation fracture for several material systems, including: equiatomic Nickel-Titanium, Nickel-Titanium-Hafnium (a high temperature SMA), and Nickel-rich Nickel-Titanium.

10172-13, Session 4

Gust prediction via artificial hair sensor array and neural network

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Gust Load Alleviation (GLA) is an important aspect of flight dynamics and control that reduces structural loadings and enhances ride quality. In conventional GLA systems, the structural response to aerodynamic excitation informs the control scheme. A phase lag, imposed by inertia, between the excitation and the measurement inherently limits the effectiveness of these systems. Hence, direct measurement of the aerodynamic loading can eliminate this lag, providing valuable information for effective GLA system design.

Distributed arrays of artificial hair sensors are ideal for surface flow measurements that can be used to predict other necessary parameters such as aerodynamic forces, moments, and turbulence. In previous work, the spatially distributed surface flow velocities obtained from an array of artificial hair sensors using feedforward neural network were found to be effective in estimating the steady aerodynamic parameters such as air speed, angle of attack, lift and moment coefficient. This paper extends the investigation of the same configuration to unsteady force and moment estimation, which is important for active GLA control design. Due to their high bandwidth, it is expected that the hair sensor array will be capable of capturing gust disturbances with a wide range of both frequency and amplitude. The gust magnitude will be then estimated as an effective change in angle of attack by a neural network trained with quasi-steady data.

This diverse, localized information can thus be directly implemented into a control scheme that alleviate the gusts without waiting for a structural response or requiring sensor calibration.

10172-14, Session 4

A new piezo-actuated compliant mechanism with self-tuned flexure arm

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Benefited from high resolution, large output force, fast dynamic response of piezoelectric actuators and displacement amplification/guiding function of flexure-based compliant mechanisms without wear, backlash or friction,

piezo-actuated compliant mechanisms have currently emerged as the most widely and popularly used ultra-precision driving and positioning technology for applications in atomic force microscopes (AFM), optical alignment, precision machining, nanoscale object manipulations, and so on. Recent interests and demands for developing video-rate AFM, high-throughput probe-based nanofabrication and high-frequency vibration generator for assisted-machining are posing new challenges for design and control of high-bandwidth and large-range compliant mechanisms. And the previous studies mainly focused on making the trade-off between natural frequency and motion range by designing a proper topology. Differing from the previous works, this paper attempts to break the deadlock by employing piezo-stacks and piezoelectric patches to actuate the compliant mechanisms. In this method, piezo-stacks provide an actuating force similar to the traditional way, while piezoelectric patches are bonded on the surface of the flexure arms in compliant mechanisms. These 'active' laminates are used to actuate the hosting flexural beam by inducing strains on the interface and then give additional bending moments to the flexural arms, which enlarge the output displacement of the compliant mechanisms. An analytical formulation is derived for modeling the compound static behaviour of a specific hybrid piezo-actuated rhombus-type compliant mechanism based on the well-known pseudo-rigid-body model and elastic beam theory. Initial simulations by the analytical model and finite element analysis verify the feasibility of the method. Further research includes designing a prototype and experimentally testing the new idea.

10172-15, Session 4

Research and development of energy harvesting from vibrations and human motions

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Most of the ambient energy, which was regarded useless in the past, now is under the spotlight. With the rapid developments on low power electronics, future personal mobile devices and remote sensing systems might become self-powered by scavenging energy in different forms from their surroundings. Kinetic energy is one of the promising energy forms in our living environment, e.g., human motions and vibrations. We have proposed an energy flow to clarify the functions of piezoelectric energy harvesting, dissipation, and their effects on the structural damping of vibrating structures. Impedance modeling and analysis were performed. We have designed an improved self-powered switching interface for piezoelectric energy harvesting circuits. With electromagnetic transduction, we also proposed a knee-mounted energy harvester that could convert the mechanical power from knee joints into electricity during walking. On the other hand, we have developed magnetorheological (MR) fluid devices with multiple functions, including rotary actuators and linear dampers. Multifunctional rotary actuator was designed to integrate motor/generator part and MR fluids into a single device. The actuator could function as motor, generator, clutch and brake, with compact size and good energy efficiency. In addition, novel self-sensing MR dampers with power generation, so as to integrate the dynamic sensing, controllable damping and power generation functions, were developed and investigated. Prototypes were fabricated and tested. The developed actuators were promising for various applications. In this paper, related research in energy harvesting done at The Chinese University of Hong Kong and key results will be presented.

10172-16, Session 4

Analytical and finite element performance evaluation of embedded piezoelectric sensors in polyethylene

Mohsen Safaei, Steven R. Anton, Tennessee Technological Univ. (United States)

A common application of piezoelectric transducers is to obtain operational data from working structures and dynamic components. This information can then be used to evaluate dynamic characterization of the system, perform structural health monitoring, or implement various other assessments. In some applications piezoelectric transducers are bonded inside the host structure to satisfy system requirements; for example, the piezoelectric transducers can be embedded inside the biopolymers of total joint replacements to evaluate the functionality of the artificial joint as well as for enabling data acquisition. The interactions between the piezoelectric device and the surrounding matrix determine the electromechanical behavior of both the matrix and the sensor. In this work, an analytical approach is employed to evaluate the electromechanical performance of axisymmetric piezoelectric elements of both spherical and cylindrical geometry. These piezoelectric elements are embedded inside the medical grade ultra-high molecular polyethylene (UHMW) bearing of a total knee replacement (TKR). Using the famous Eshelby inhomogeneity solution, the electrical output of the spherical piezoelectric geometry is obtained by decoupling the problem into purely elastic and purely dielectric systems of equations. For the cylindrical geometry, an approximation method based on the boundary integral function is utilized and the same decoupling method is employed. In order to validate the analytical result, a finite element analysis is performed for both the spherical and cylindrical geometries and the error for each case is calculated.

10172-17, Session 5

On the distributed observer/controller strategy for disturbance rejection

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Centralized controllers and state estimation strategies are the most common topology implemented for disturbance rejection in smart systems. Although this architecture has been proven to be feasible the advances in computation power and size of logic devices can also enable the implementation of distributed strategies which, on a large scale, can lead to an overall reliability increase of the system. The goal of this paper is to present this concept within the field of disturbance rejection for smart systems and to explore its capabilities and bottlenecks. A simple example is carried out for a composite plate with two controller/estimator centers. Both simulation and experimental tests are used to validate the efficacy of the topology and a design procedure is proposed to guarantee the consensus of the agents within the network.

10172-18, Session 5

Simultaneous passive broadband vibration suppression and energy harvesting with metastructures

Jared D. Hobeck, Daniel J. Inman Sr., Univ. of Michigan (United States)

The research presented in this paper focuses on a unique multifunctional structural design that not only absorbs vibration at desired frequency bands, but also extracts significant amounts of electrical energy. This is accomplished by first designing an array of low-frequency resonators to be integrated into a larger host structure. This array of resonators can contribute not only to static requirements, e.g., stiffness, strength, mass, etc., of the host structure but the array also functions as a distributed system of passive vibration absorbers. Structures having these distributed vibration absorber systems are known as metastructures. Here, the authors present a unique absorber design referred to as a zigzag beam, which can have a natural frequency an order of magnitude lower than that of a basic cantilever beam of the same scale. It will be shown that the zigzag beams can be designed with an added layer of piezoelectric material which allows them to harvest significant amounts of electrical power as

they suppress vibration of the host structure. This paper includes details of the fully-coupled electromechanical analytical and numerical models for energy harvesting metastructures. Experimental results used to validate the proposed modeling methods will be discussed. Lastly, results of a multi-objective design optimization will be presented and discussed. Initial optimization results show that allowing the structural response to increase by 25% produces a 500% increase in harvested power.

10172-19, Session 5

Piezoelectric interfaces enabled energy harvesting and tailored damping in fiber composites

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Fiber reinforced polymer composites are becoming ubiquitous in modern structures, due to their light weight, high specific strength, and ability to be tailored for a specific application. The increase in the commercial adoption and feasible applications of composite materials has motivated researchers to develop next generation of composites. These next generation composites aim to integrate more structural and nonstructural properties into the structure with the goal of increasing the efficiency of the system as a whole. There have been many efforts in modifying or replacing structural fiber and matrix phases with active materials. However, this methodology usually affects the structural properties of the composite and limits their practical applications. Here, we present a new approach for the development of multifunctional fiber reinforced polymer composites. In this method, piezoelectric nanostructures (ZnO nanowires and barium titanate textured films) are integrated at the interface between structural fibers and matrix phase. Since the load transfer between reinforcement phase and polymer matrix happens at the interfacial region, the active phase at the interface result in a composite with unique properties. In this study we examined the vibration damping and energy harvesting of the fabricated composites. The nanostructured interface showed a great potential as a damping mechanism and energy harvesting constituent in these composites. The large amount of stress concentration in this region resulted in increased damping properties and sustainable energy harvesting performance. This research introduces a route for integrating responsive properties into structural composites by utilizing functional nanostructured interfaces.

10172-20, Session 5

Two score years less five of an Anglo-American Special Relationship in Structural Dynamics (AASRSD)

David J. Ewins, Imperial College London (United Kingdom)

This paper reviews some of the highlights of the other anglo-american ‘special relationship’: the one in structural dynamics. The milestones in the history of this relationship, which spans some 35 years (half of three score years and ten), are a number of international conferences attended by two of the longest serving players in the AASRSD – one from the USA and one from the UK. The overall strategy which is addressed by this series of encounters will be discussed and illustrated by a joint account of selected case studies.