Smart Materials and Structures
Highlights of 2014

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Natasha Leeper
Publisher
Smart Materials and Structures

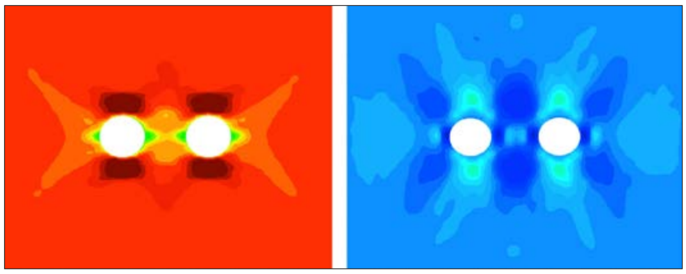
Plastic and transformation interactions of pores in shape memory alloy plates

Pingping Zhu[1], Aaron P Stebner[2] and L Catherine Brinson[1]

[1] Mechanical Engineering, Northwestern University, Evanston, USA
[2] Mechanical Engineering, Colorado School of Mines, Golden, USA

Abstract
A three-dimensional constitutive model for shape memory alloys (SMAs) is developed along the lines of the Stebner–Brinson (SB) implementation of the Panico–Brinson model. Plastic kinematic hardening behavior is simulated in addition to elastic deformation and phase transformation. A series of finite element simulations is carried out using this model to investigate the localization effects of the stress and strain field on NiTi plates with structured arrays of pores. The application of this model on porous architectures provides insight into how geometric features influence the mechanics of the structure. The incorporation of plastic deformation shows a marked decrease in the maximum stress levels; these results are more consistent with experimental data as compared to the original SB model. Furthermore, the new results demonstrate that clustered pores lead to more distributed stresses and transformation compared to a dispersed configuration of pores, indicating the importance of pore geometry in determining the stress and strain distribution. The improved model provides a practical tool toward design and optimization of porous SMA structures.

2014 *Smart Mater. Struct.* **23** 104008



Artificial linear superposition result of two pores from the single-pore simulation results: (left) axial stress and (right) transverse stress.

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Flexible piezoelectric energy harvesting from jaw movements

Aidin Delnavaz and Jérémie Voix

Mechanical Engineering Department, École de technologie supérieure (ÉTS), Montreal, Canada

Abstract
Piezoelectric fiber composites (PFC) represent an interesting subset of smart materials that can function as sensor, actuator and energy converter. Despite their excellent potential for energy harvesting, very few PFC mechanisms have been developed to capture the human body power and convert it into an electric current to power wearable electronic devices. This paper provides a proof of concept for a head-mounted device with a PFC chin strap capable of harvesting energy from jaw movements. An electromechanical model based on the bond graph method is developed to predict the power output of the energy harvesting system. The optimum resistance value of the load and the best stretch ratio in the strap are also determined. A prototype was developed and tested and its performances were compared to the analytical model predictions. The proposed piezoelectric strap mechanism can be added to all types of head-mounted devices to power small-scale electronic devices such as hearing aids, electronic hearing protectors and communication earpieces.

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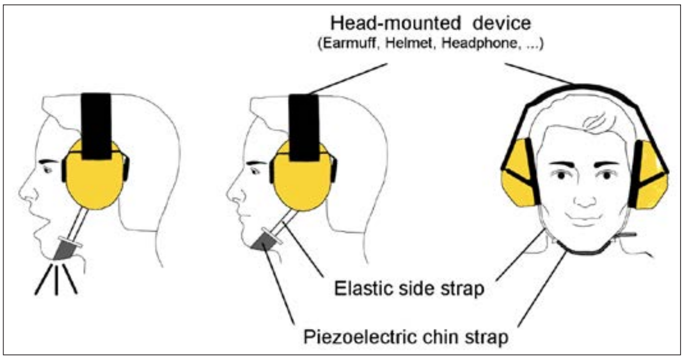

Jaw movement energy harvester.

Variation in the mechanical properties of tracheal tubes in the American cockroach

Winston R Becker, Matthew R Webster, John J Socha and Raffaella De Vita

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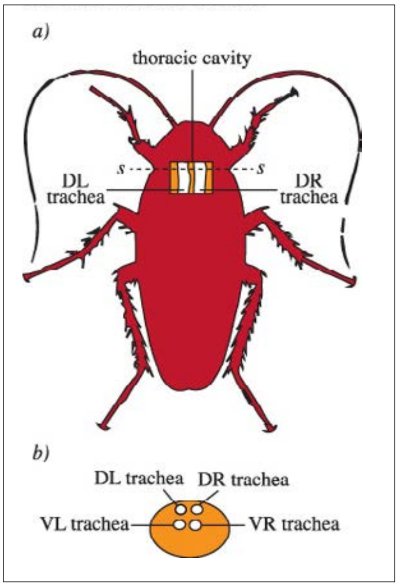
Abstract
The insect cuticle serves the protective role of skin and the supportive role of the skeleton while being lightweight and flexible to facilitate flight. The smart design of the cuticle confers camouflage, thermo-regulation, communication, self-cleaning, and anti-wetting properties to insects. The mechanical behavior of the internal cuticle of the insect in tracheae remains largely unexplored due to their small size. In order to characterize the material properties of insect tracheae and understand their role during insect respiration, we conducted tensile tests on ring sections of tracheal tubes of American cockroaches (Periplaneta americana). A total of 33 ring specimens collected from 14 tracheae from the upper thorax of the insects were successfully tested. The ultimate tensile strength (22.6 ± 13.3 MPa), ultimate strain (1.57 ± 0.68%), elastic modulus (1740 ± 840 MPa), and toughness (0.175 ± 0.156 MJ m^{-3}) were measured. We examined the high variance in mechanical properties statistically and demonstrated that ring sections excised from the same trachea exhibit comparable mechanical properties. Our results will form the basis for future studies aimed at determining the structure–function relationship of insect tracheal tubes, ultimately inspiring the design of multi-functional materials and structures.

2014 *Smart Mater. Struct.* **23** 057001



Schematic of the American cockroach and the four main thoracic tracheal trunks (a) top view (b) cross section.

Smart fabric sensors and e-textile technologies: a review

Lina M Castano and Alison B Flatau

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Abstract
This paper provides a review of recent developments in the rapidly changing and advancing field of smart fabric sensor and electronic textile technologies. It summarizes the basic principles and approaches employed when building fabric sensors as well as the most commonly used materials and techniques used in electronic textiles. This paper shows that sensing functionality can be created by intrinsic and extrinsic modifications to textile substrates depending on the level of integration into the fabric platform. The current work demonstrates that fabric sensors can be tailored to measure force, pressure, chemicals, humidity and temperature variations. Materials, connectors, fabric circuits, interconnects, encapsulation and fabrication methods associated with fabric technologies prove to be customizable and versatile but less robust than their conventional electronics counterparts. The findings of this survey suggest that a complete smart fabric system is possible through the integration of the different types of textile based functional elements. This work intends to be a starting point for standardization of smart fabric sensing techniques and e-textile fabrication methods.

2014 *Smart Mater. Struct.* **23** 053001

Flexible pressure sensors for smart protective clothing against impact loading

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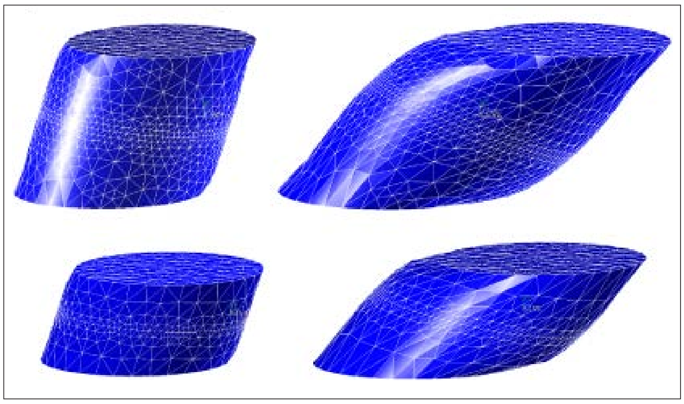
Abstract
The development of smart protective clothing will facilitate the quick detection of injuries from contact sports, traffic collisions and other accidents. To obtain real-time information like spatial and temporal pressure distributions on the clothing, flexible pressure sensor arrays are required. Based on a resistive fabric strain sensor we demonstrate all flexible, resistive pressure sensors with a large workable pressure range (0–8 MPa), a high sensitivity (1 MPa^{-1}) and an excellent repeatability (lowest non-repeatability ±2.4% from 0.8 to 8 MPa) that can be inexpensively fabricated using fabric strain sensors and biocompatible polydimethylsiloxane (PDMS). The pressure sensitivity is tunable by using elastomers with different elasticities or by the pre-strain control of fabric strain sensors. Finite element simulation further confirms the sensor design. The simple structure, large workable pressure range, high sensitivity, high flexibility, facile fabrication and low cost of these pressure sensors make them promising candidates for smart protective clothing against impact loading.

2014 *Smart Mater. Struct.* **23** 015001



Selected screenshots in FEA of sensor shear.

Origami interleaved tube cellular materials

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2 Department of General Systems Studies, The University of Tokyo, Japan

3 Massachusetts Institute of Technology, Center for Bits and Atoms, Cambridge, USA

4 Professor Emeritus, The University of Tokyo, Japan

Abstract
A novel origami cellular material based on a deployable cellular origami structure is described. The structure is bi-directionally flat-foldable in two orthogonal (x and y) directions and is relatively stiff in the third orthogonal (z) direction. While such mechanical orthotropicity is well known in cellular materials with extruded two dimensional geometry, the interleaved tube geometry presented here consists of two orthogonal axes of interleaved tubes with high interfacial surface area and relative volume that changes with fold-state. In addition, the foldability still allows for fabrication by a flat lamination process, similar to methods used for conventional expanded two dimensional cellular materials. This article presents the geometric characteristics of the structure together with corresponding kinematic and mechanical modeling, explaining the orthotropic elastic behavior of the structure with classical dimensional scaling analysis.

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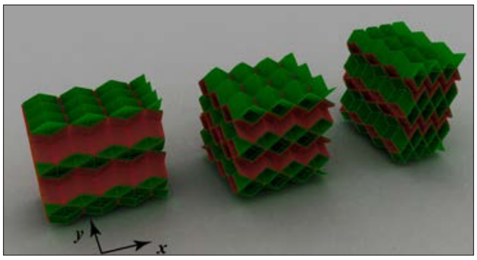

Cellular structure actuated by differentially pressurizing two sets of tubes in x and y directions.

Three-dimensional microstructural investigation of high magnetization nano–micro composite fluids using x-ray microcomputed tomography

T Borbáth[1,2], I Borbáth[2], S Günther[1], O Marinica[3], L Vékás[4] and S Odenbach[1]

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2 Roseal Corporation, Odorheiu Secuiesc, Romania

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4 Romanian Academy, Timisoara Branch, Center for Fundamental and Advanced Technical Research, Laboratory of Magnetic Fluids, Romania

Abstract
X-ray microcomputed tomography was used in a three-dimensional investigation of the microstructure of suspensions of multi-domain soft iron particles in magnetic nanofluids. The measurements were performed using two different approaches: with the sample kept frozen, and with the sample under the effect of an external magnetic field. Results show that even a relatively low magnetic field gradient drives the micron-sized iron particles towards the stronger field and thus leads to a redistribution of the ferromagnetic particles in the magnetic nanofluid. Three-dimensional images of the internal microstructure of the composite magnetizable fluid (CMF) were obtained not only for the nano–micro composite system placed in a closed sample holder, but also for the spikes formed at the CMF free surface. It was demonstrated that x-ray microcomputed tomography is an efficient way to investigate the distribution and chain formation of ferromagnetic microparticles in a magnetic nanofluid carrier allowing an analysis even at a single particle level.

2014 *Smart Mater. Struct.* **23** 055018

Reconstructed tomography images of CMF spikes.

Energy harvester for rotating environments using offset pendulum and nonlinear dynamics

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[2] J2La, Inc., Las Vegas, USA

Abstract

We present an energy harvester for environments that rotate through the Earth's gravitational field. Example applications include shafts connected to motors, axles, propellers, fans, and wheels or tires. Our approach uses the unique dynamics of an offset pendulum along with a nonlinear bistable restoring spring to improve the operational bandwidth of the system. Depending on the speed of the rotating environment, the system can act as a bistable oscillator, monostable stiffening oscillator, or linear oscillator. We apply our approach to a tire pressure monitoring system mounted on a car rim. Simulation and experimental test results show that the prototype generator is capable of directly powering an RF transmission every 60 s or less over a speed range of 10 to 155 kph.

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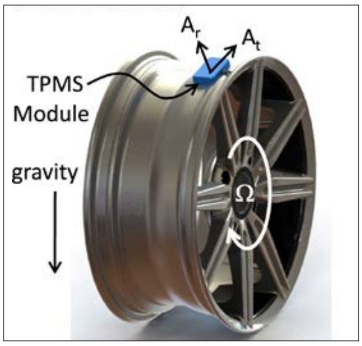

Tire pressure monitoring system (TPMS) module mounted to a rim.

Enhanced hydrodynamic performance of flexible fins using macro fiber composite actuators

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Abstract

Recent studies on the role of body flexibility in propulsion suggest that fish have the ability to control the shape or modulate the stiffness of the fins for optimized performance. Inspired by nature's ability to modulate stiffness and shape for different operating conditions, this paper investigates active control of flapping foils for thrust tailoring using Macro Fiber Composites (MFCs). A coupled piezohydroelastic model has been developed to predict the propulsive performance of an actively deforming fin. The effect of important parameters such as oscillation frequency, flexibility of the fin, applied voltage and the phase difference between applied voltage and heaving on propulsive performance are studied and reported. It is observed that distributed actuation along fin produces maximum performance through proper selection of the phase difference between heaving and voltage. The optimal phase for lower values of fin stiffness is approximately 90° and it approaches 0° for higher stiffness values. Experiments performed to determine the effect of active control using MFCs validate the theoretical results.

2014 *Smart Mater. Struct.* **23** 115012

Direct-write PVDF nonwoven fiber fabric energy harvesters via the hollow cylindrical near-field electrospinning process

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Abstract

One-dimensional piezoelectric nanomaterials have attracted great attention in recent years for their possible applications in mechanical energy scavenging devices. However, it is difficult to control the structural diameter, length, and density of these fibers fabricated by micro/nano-technologies. This work presents a hollow cylindrical near-field electrospinning (HCNFES) process to address production and performance issues encountered previously in either far-field electrospinning (FFES) or near-field electrospinning (NFES) processes. Oriented polyvinylidene fluoride (PVDF) fibers in the form of nonwoven fabric have been directly written on a glass tube for aligned piezoelectricity. Under a high *in situ* electrical poling field and strong mechanical stretching (the tangential speed on the glass tube collector is about 1989.3 mm s^{-1}), the HCNFES process is able to uniformly deposit large arrays of PVDF fibers with good concentrations of piezoelectric β-phase. The nonwoven fiber fabric (NFF) is transferred onto a polyethylene terephthalate (PET) substrate and fixed at both ends using copper foil electrodes as a flexible textile-fiber-based PVDF energy harvester. Repeated stretching and releasing of PVDF NFF with a strain of 0.05% at 7 Hz produces a maximum peak voltage and current at 76 mV and 39 nA, respectively.

2014 *Smart Mater. Struct.* **23** 025003

Wearable thermoelectric generator for harvesting human body heat energy

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Abstract

This paper presents the realization of a wearable thermoelectric generator (TEG) in fabric for use in clothing. A TEG was fabricated by dispenser printing

of $Bi_{0.5}Sb_{1.5}Te_3$ and $Bi_2Se_{0.3}Te_{2.7}$ in a polymer-based fabric. The prototype consisted of 12 thermocouples connected by conductive thread over an area of 6 × 25 mm². The device generated a power of 224 nW for a temperature difference of 15 K. When the TEG was used on the human body, the measured output power was 224 nW in an ambient temperature of 5 °C. The power of the TEG was affected by the movement of the wearer. A higher voltage was maintained while walking than in a stationary state. In addition, the device did not deform after it was bent and stretched several times. The prospect of using the TEG in clothing applications was confirmed under realistic conditions.

2014 *Smart Mater. Struct.* **23** 105002

Bio-inspired structural bistability employing elastomeric origami for morphing applications

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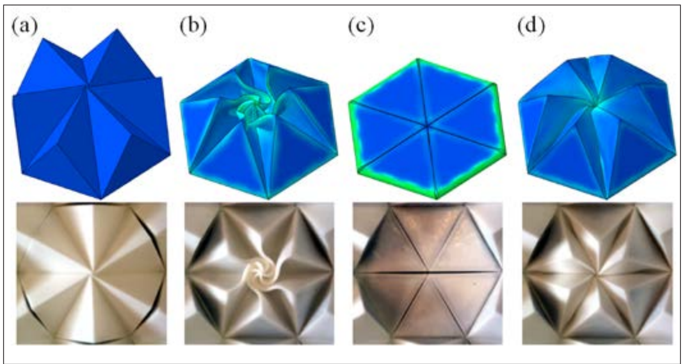
Abstract
A structural concept based upon the principles of adaptive morphing cells is presented whereby controlled bistability from a flat configuration into a textured arrangement is shown. The material consists of multiple cells made from silicone rubber with locally reinforced regions based upon kirigami principles. On pneumatic actuation these cells fold or unfold based on the fold lines created by the interaction of the geometry with the reinforced regions. Each cell is able to maintain its shape in either a retracted or deployed state, without the aid of mechanisms or sustained actuation, due to the existence of structural bistability. Mathematical quantification of the surface texture is introduced, based on out-of-plane deviations of a deployed structure compared to a reference plane. Additionally, finite element analysis is employed to characterize the geometry and stability of an individual cell during actuation and retraction. This investigation highlights the critical role that angular rotation, at the center of each cell, plays on the deployment angle as it transitions through the elastically deployed configuration. The analysis of this novel concept is presented and a pneumatically actuated proof-of-concept demonstrator is fabricated.

2014 *Smart Mater. Struct.* **23** 125011



Maximum principal strains in the hexagonal cell from FE analysis and the geometries of the manufactured demonstrator; (a) deployed state, (b) transition from deployed to retracted state, (c) retracted state, (d) transition from retracted to deployed state.

Shape memory polymers and their composites in aerospace applications: a review

Yanju Liu, Haiyang Du, Liwu Liu and Jinsong Leng

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Abstract
As a new class of smart materials, shape memory polymers and their composites (SMPs and SMPCs) can respond to specific external stimulus and remember the original shape. There are many types of stimulus methods to actuate the deformation of SMPs and SMPCs, of which the thermal- and electro-responsive components and structures are common. In this review, the general mechanism of SMPs and SMPCs are first introduced, the stimulus methods are then discussed to demonstrate the shape recovery effect, and finally, the applications of SMPs and SMPCs that are reinforced with fiber materials in aerospace are reviewed. SMPC hinges and booms are discussed in the part on components; the booms can be divided again into foldable SMPC truss booms, coilable SMPC truss booms and storable tubular extendible member (STEM) booms. In terms of SMPC structures, the solar array and deployable panel, reflector antenna and morphing wing are introduced in detail. Considering the factors of weight, recovery force and shock effect, SMPCs are expected to have great potential applications in aerospace.

2014 *Smart Mater. Struct.* **23** 023001

Magnetorheology of dimorphic magnetorheological fluids based on nanofibers

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[2] Department of Applied Physics, University of Granada, Spain

Abstract
We report a systematic experimental investigation on the use of nanofibers to enhance the magnetorheological (MR) effect in conventional (microsphere-based) MR fluids formulated in polyalphaolefin oil/1-octanol. Two kinds of nanofibers are employed that have very similar morphology but very different magnetic properties. On the one hand we use non-magnetic goethite nanofibers. On the other hand we employ magnetic chromium dioxide nanofibers. For appropriate concentrations the on-state relative yield stress increases up to 80% when incorporating the nanofibers in the formulation. A similar yield stress enhancement is found for both nanofibers investigated (magnetic and non-magnetic) suggesting that the main factor behind this MR enhancement is the particle shape anisotropy. The relative yield stresses obtained by partial substitution of carbonyl iron particles with nanofibers are significantly larger than those measured in previous works on MR fluids formulated by partial substitution with non-magnetic micronized spherical particles. We also demonstrate that these dimorphic MR fluids also exhibit remarkably larger long-term sedimentation stability while keeping the same penetration and redispersibility characteristics.

2014 *Smart Mater. Struct.* **23** 125013

A novel triple-actuating mechanism of an active air mount for vibration control of precision manufacturing machines: experimental work

Hyung-Tae Kim[1], Cheol-Ho Kim[1], Seung-Bok Choi[2], Seok-Jun Moon[3] and Won-Gil Song[4]

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[2] Smart Structures and Systems Laboratory, Inha University, South Korea

[3] Shock and Vibration Team, KIMM, Daejeon, South Korea

[4] Structure Dynamic Design Group, RMS Technology, Cheonan, South Korea

Abstract

With the goal of vibration control and isolation in a clean room, we propose a new type of air mount which consists of pneumatic, electromagnetic (EM), and magnetorheological (MR) actuators. The air mount is installed below a semiconductor manufacturing machine to reduce the adverse effects caused by unwanted vibration. The proposed mechanism integrates the forces in a parallel connection of the three actuators. The MR part is designed to operate in an air spring in which the EM part is installed. The control logic is developed with a classical method and a switching mode to avoid operational mismatch among the forces developed. Based on extended microprocessors, a portable, embedded controller is installed to execute both nonlinear logic and digital communication with the peripherals. The pneumatic forces constantly support the heavy weight of an upper structure and maintain the level of the air mount. The MR damper handles the transient response, while the EM controller reduces the resonance response, which is switched mutually with a threshold. Vibration is detected by laser displacement sensors which have submicron resolution. The impact test results of three tons load weight demonstrate practical feasibility by showing that the proposed triple-actuating mechanism can reduce the transient response as well as the resonance in the air mount, resulting in accurate motion of the semiconductor manufacturing machine.

2014 *Smart Mater. Struct.* **23** 077003

A quantum informed continuum model for ferroelectric materials

William Oates

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Abstract

Quantum mechanical stress relations are studied to guide the development of a continuum scale electromechanical constitutive model for ferroelectric materials. Stresses at the quantum scale are determined through the use of the Hellmann–Feynman theorem to obtain an electrostatic stress that depends on the electric quadrupole density as opposed to polarization dependent electrostriction. The result is integrated into a continuum model using a generalized set of electronic coordinate vector order parameters contained within a Lagrangian density formulation. The new constitutive model is shown to be consistent with both quantum based stress and classical phenomenological electrostriction. This conclusion is verified through a numerical study of lead titanate where calculations of energy, stress and polarization from density functional theory (DFT) are fit to continuum stored energy and electrostatic stresses. The numerical analysis includes uncertainty quantification using Bayesian statistics to gain further insight into material parameter uncertainty when approximating DFT calculations as a reduced-order continuum model.

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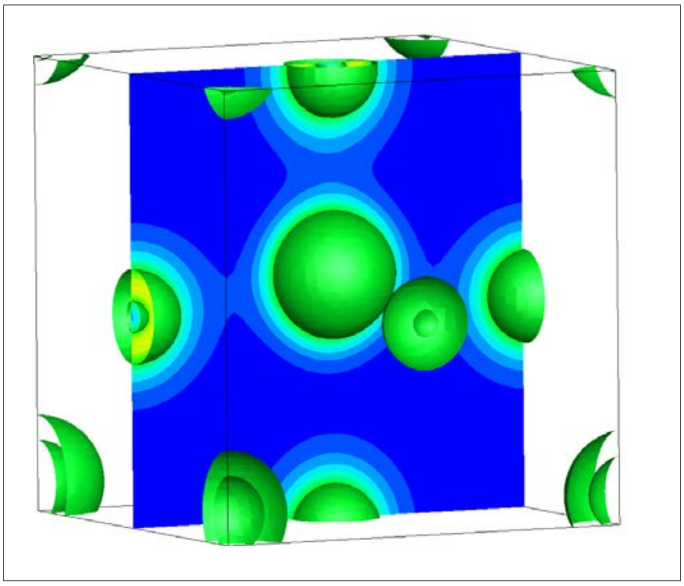

Plot of the electron density within a unit cell of lead titanate at the lowest energy tetragonal state. Titanium is the center atom and lead is on each corner.

A review of piezoelectric polymers as functional materials for electromechanical transducers

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Abstract

Polymer based MEMS and microfluidic devices have the advantages of mechanical flexibility, lower fabrication cost and faster processing over silicon based ones. Also, many polymer materials are considered biocompatible and can be used in biological applications. A valuable class of polymers for microfabricated devices is piezoelectric functional polymers. In addition to the normal advantages of polymers, piezoelectric polymers can be directly used as an active material in different transduction applications. This paper gives an overview of piezoelectric polymers based on their operating principle. This includes three main categories: bulk piezoelectric polymers, piezocomposites and voided charged polymers. State-of-the-art piezopolymers of each category are presented with a focus on fabrication techniques and material properties. A comparison between the different piezoelectric polymers and common inorganic piezoelectric materials (PZT, ZnO, AlN and PMN–PT) is also provided in terms of piezoelectric properties. The use of piezopolymers in different electromechanical devices is also presented. This includes tactile sensors, energy harvesters, acoustic transducers and inertial sensors.

2014 *Smart Mater. Struct.* **23** 033001

A review on shape memory alloys with applications to morphing aircraft

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[2] Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile, Santiago, Chile

[3] Aeronautics and Astronautics, University of Southampton, UK

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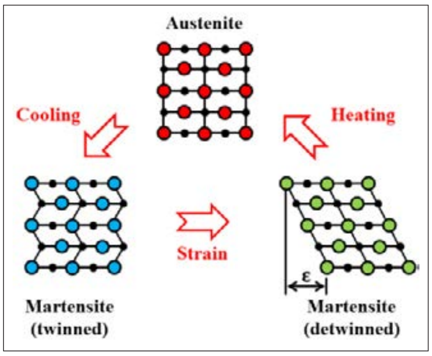
Abstract

Shape memory alloys (SMAs) are a unique class of metallic materials with the ability to recover their original shape at certain characteristic temperatures (shape memory effect), even under high applied loads and large inelastic deformations, or to undergo large strains without plastic deformation or failure (super-elasticity). In this review, we describe the main features of SMAs, their constitutive models and their properties. We also review the fatigue behavior of SMAs and some methods adopted to remove or reduce its undesirable effects. SMAs have been used in a wide variety of applications in different fields. In this review, we focus on the use of shape memory alloys in the context of morphing aircraft, with particular emphasis on variable twist and camber, and also on actuation bandwidth and reduction of power consumption. These applications prove particularly challenging because novel configurations are adopted to maximize integration and effectiveness of SMAs, which play the role of an actuator (using the shape memory effect), often combined with structural, load-carrying capabilities. Iterative and multi-disciplinary modeling is therefore necessary due to the fluid–structure interaction combined with the nonlinear behavior of SMAs.

2014 *Smart Mater. Struct.* **23** 063001



Microscopic phenomenology associated with the shape memory effect

Highlights of 2013

You can view the *Smart Materials and Structures* Highlights of 2013 at **http://iopscience.iop.org/0964-1726/page/Highlights of 2013**

A state-of-the-art review on magnetorheological elastomer devices

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[2] School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Australia

[3] School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Australia

Abstract

During the last few decades, magnetorheological (MR) elastomers have attracted a significant amount of attention for their enormous potential in engineering applications. Because they are a solid counterpart to MR fluids, MR elastomers exhibit a unique field-dependent material property when exposed to a magnetic field, and they overcome major issues faced in magnetorheological fluids, e.g. the deposition of iron particles, sealing problems and environmental contamination. Such advantages offer great potential for designing intelligent devices to be used in various engineering fields, especially in fields that involve vibration reduction and isolation. This paper presents a state of the art review on the recent progress of MR elastomer technology, with special emphasis on the research and development of MR elastomer devices and their applications. To keep the integrity of the knowledge, this review includes a brief introduction of MR elastomer materials and follows with a discussion of critical issues involved in designing magnetorheological elastomer devices, i.e. operation modes, coil placements and principle fundamentals. A comprehensive review has been presented on the research and development of MR elastomer devices, including vibration absorbers, vibration isolators, base isolators, sensing devices, and so on. A summary of the research on the modeling mechanical behavior for both the material and the devices is presented. Finally, the challenges and the potential facing magnetorheological elastomer technology are discussed, and suggestions have been made based on the authors' knowledge and experience.

2014 *Smart Mater. Struct.* **23** 123001

Impact damage detection in light composite sandwich panels using piezo-based nonlinear vibro-acoustic modulations

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Abstract

The nonlinear vibro-acoustic modulation technique is used for impact damage detection in light composite sandwich panels. The method utilizes piezo-based low-frequency vibration and high-frequency ultrasonic excitations. The work presented focuses on the analysis of modulation intensity. The results show that the method can be used for impact damage detection reliably separating damage-related from vibro-acoustic modulations from other intrinsic nonlinear modulations.

2014 *Smart Mater. Struct.* **23** 105021

Active origami by 4D printing

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[3] Department of Engineering, Colorado State University, USA

[4] School of Mechanical Engineering, Georgia Institute of Technology, USA

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Abstract

Recent advances in three dimensional (3D) printing technology that allow multiple materials to be printed within each layer enable the creation of materials and components with precisely controlled heterogeneous microstructures. In addition, active materials, such as shape memory polymers, can be printed to create an active microstructure within a solid. These active materials can subsequently be activated in a controlled manner to change the shape or configuration of the solid in response to an environmental stimulus. This has been termed 4D printing, with the 4th dimension being the time-dependent shape change after the printing. In this paper, we advance the 4D printing concept to the design and fabrication of active origami, where a flat sheet automatically folds into a complicated 3D component. Here we print active composites with shape memory polymer fibers precisely printed in an elastomeric matrix and use them as intelligent active hinges to enable origami folding patterns. We develop a theoretical model to provide guidance in selecting design parameters such as fiber dimensions, hinge length, and programming strains and temperature. Using the model, we design and fabricate several active origami components that assemble from flat polymer sheets, including a box, a pyramid, and two origami airplanes. In addition, we directly print a 3D box with active composite hinges and program it to assume a temporary flat shape that subsequently recovers to the 3D box shape on demand.

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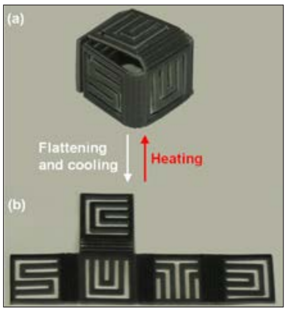

A directly printed origami SUTD-CU box. An as-printed 3D SUTD-CU box in (a) was deformed into a flat form at T_L in (b). After heating back to T_H, the structure recovers the 3D box shape.

Origami-inspired active structures: a synthesis and review

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Abstract

Origami, the ancient art of paper folding, has inspired the design of engineering devices and structures for decades. The underlying principles of origami are very general, which has led to applications ranging from cardboard containers to deployable space structures. More recently, researchers have become interested in the use of active materials (i.e., those that convert various forms of energy into mechanical work) to effect the desired folding behavior. When used in a suitable geometry, active materials allow engineers to create self-folding structures. Such structures are capable of performing folding and/or unfolding operations without being kinematically manipulated by external forces or moments. This is advantageous for many applications including space systems, underwater robotics, small scale devices, and self-assembling systems. This article is a survey and analysis of prior work on active self-folding structures as well as methods and tools available for the design of folding structures in general and self-folding structures in particular. The goal is to provide researchers and practitioners with a systematic view of the state-of-the-art in this important and evolving area. Unifying structural principles for active self-folding structures are identified and used as a basis for a quantitative and qualitative comparison of numerous classes of active materials. Design considerations specific to folded structures are examined, including the issues of crease pattern identification and fold kinematics. Although few tools have been created with active materials in mind, many of them are useful in the overall design process for active self-folding structures. Finally, the article concludes with a discussion of open questions for the field of origami-inspired engineering.

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Multi-fingered haptic palpation utilizing granular jamming stiffness feedback actuators

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Abstract

This paper describes a multi-fingered haptic palpation method using stiffness feedback actuators for simulating tissue palpation procedures in traditional and in robot-assisted minimally invasive surgery. Soft tissue stiffness is simulated by changing the stiffness property of the actuator during palpation. For the first time, granular jamming and pneumatic air actuation are combined to realize stiffness modulation. The stiffness feedback actuator is validated by stiffness measurements in indentation tests and through stiffness discrimination based on a user study. According to the indentation test results, the introduction of a pneumatic chamber to granular jamming can amplify the stiffness variation range and reduce hysteresis of the actuator. The advantage of multi-fingered palpation using the proposed actuators is proven by the comparison of the results of the stiffness discrimination performance using two-fingered (sensitivity: 82.2%, specificity: 88.9%, positive predicative value: 80.0%, accuracy: 85.4%, time: 4.84 s) and single-fingered (sensitivity: 76.4%, specificity: 85.7%, positive predicative value: 75.3%, accuracy: 81.8%, time: 7.48 s) stiffness feedback.

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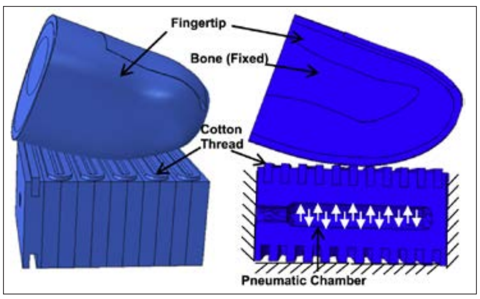

3D modeling of the inflation behavior of the silicone pneumatic chamber with a fingertip contacting the top surface: (left) integral structure, (right) cross section.