Structural Health Monitoring and Self-Healing of Aerospace Structures

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Abstract

Aerospace structural systems experience a broad spectrum of environmental and operational loads. Severe and/or prolonged load exposures may trigger the damage accumulation process even in recently deployed structures. The process of implementing a strategy of damage detection for engineering structures is referred to as structural health monitoring (SHM).

Three important “new” issues/approaches impacting SHM methodology are addressed in this proposal. The first is to treat SHM as a comprehensive, multi-scale phenomenon in which damage detection may be needed over a spectrum of length scales from the microscopic to the macroscopic. The second issue is attributing to damage in joints and connections an importance commensurate with fracture and fatigue damage that develops in the structural material. Our third “new” approach is to develop material self-healing systems (SHS) capable of repairing material damage while maintaining structural integrity. The strategies proposed will be intended for many aerospace structures, including aircraft, launch vehicles, space vehicles, periodic space structures, and permanent structures placed on the moon or Mars.

The lines of attack that will be followed in pursuit of the new SHM and SHS methodologies include new methods for use of nonlinear vibration data, novel use of electrical conductivity measurements for SHM, and embedded nonlinear acoustic methods for local damage detection. In addition, development of the theory and technology for self-healing systems (SHS) in metals, alloys and composites could lead to significantly improved safety of aerospace vehicles and structures. These approaches will be integrated to develop a comprehensive SHM/SHS strategy that will be of significant value to NASA during coming decades.

Structural Health Monitoring and Self-Healing of Aerospace Structures

Introduction

Aerospace structural systems experience a broad spectrum of environmental and operational loads. Severe and/or prolonged load exposures may trigger the damage accumulation process even in recently deployed structures. The process of implementing a strategy of damage detection for engineering structures is referred to as structural health monitoring (SHM), which seeks to answer questions such as: Does damage exist? If so, what kind? Is the damage local or global (e.g., a large isolated crack or many small defects distributed in the material)? Is the damage in the material or in the joints and connections (or both)? Is overall structural failure likely?

SHM is normally based on non-destructive measurement of responses that change due to damage in the structure. Comparisons of measurements made in a damaged and in a reference state allow inference of the type, location, and severity of the damage. Historically, vibration natural frequencies and mode shapes have been the most common such measurements: macroscopic damage tends to reduce the natural frequencies, and mode shapes may be sensitive to isolated damage. Vibration measurements have been used in many ways for this purpose (Doebling, et al, 1996; Sohn, et al, 2003).

Three important "new" issues/approaches impacting structural health methodology are addressed in this proposal. The first is to treat SHM as a comprehensive, multi-scale phenomenon in which damage detection may be needed over a spectrum of length scales from the microscopic to the macroscopic. Most SHM methodologies focus only on limited length scales. The second issue is attributing to damage in joints and connections an importance commensurate with fracture and fatigue damage that develops in the structural material. During the past decade the SHM and joint dynamics communities have each done extensive research. But SHM researchers normally ignore possible damage in joints and connections, and joint analysts normally ignore SHM, as their focus is on developing nonlinear models of joint dynamics. We aim to incorporate nonlinear joint damage modeling into the SHM methodology, and this promises to be an important contribution to the science of SHM. Our third "new" approach is to develop material self-healing systems (SHS) that could repair material damage while maintaining structural integrity. For example, microencapsulated healing agents could be incorporated into a material, such that a propagating crack would burst the microcapsules, releasing the healing agent into the crack, filling the cavity and curing the crack so that failure of the material is avoided. The strategies proposed in this paragraph will be intended for many aerospace structures, including aircraft, launch vehicles, space vehicles, periodic space structures, and permanent structures placed on the moon or Mars.

There are four lines of attack that will be followed in pursuit of the aforementioned SHM and SHS methodologies; these are summarized below.

1) Development of a <u>combined joint/material nonlinear vibration-based methodology</u> that is capable of crack detection through nonlinear vibration measurement and is capable of separating material damage from joint/connection damage. The latter is necessary because changes in vibration properties that would normally be attributed to damage in the material may actually be due to change in the boundary conditions accompanying deterioration in a joint or connection.
2) Utilize recently derived results (Sevostianov and Kachanov, 2002) for the <u>cross-property connections between elastic and conductive properties of materials with defects</u>. These results allow one to measure the change in a bulk material property such as Young's modulus

by measuring the change in the material electrical conductivity. This provides an independent source of information that can be combined with the joint/material methodology in 1) above, enabling joint damage to be separated from material damage. In addition, methods for directly relating the cross-property connection results to material damage will be pursued.

3) Development of a high frequency nonlinear acoustic wave propagation SHM approach (Zagrai, et al. 2006) aimed at early, small-scale damage detection. In addition to global and some local parameters inferred through vibration measurements, the nonlinear acoustic methodology will utilize the local nonlinear response at high frequencies for damage detection by monitoring the presence of combination frequencies in the acoustic response, which signal the presence of nonlinear effects that accompany micro-damage.
4) Pursuit of the aforementioned methodology for self-healing systems (SHS) in metals, alloys and composites, which could lead to significantly increased safety of aerospace vehicles and structures. Several concepts will be developed and realized, based on the work of Bakhtiyarov and Overfelt (1997 - 2002).

Figure 1 shows how the proposed methodologies relate to each other to form a strategy that covers the spectrum of scales and damage levels.

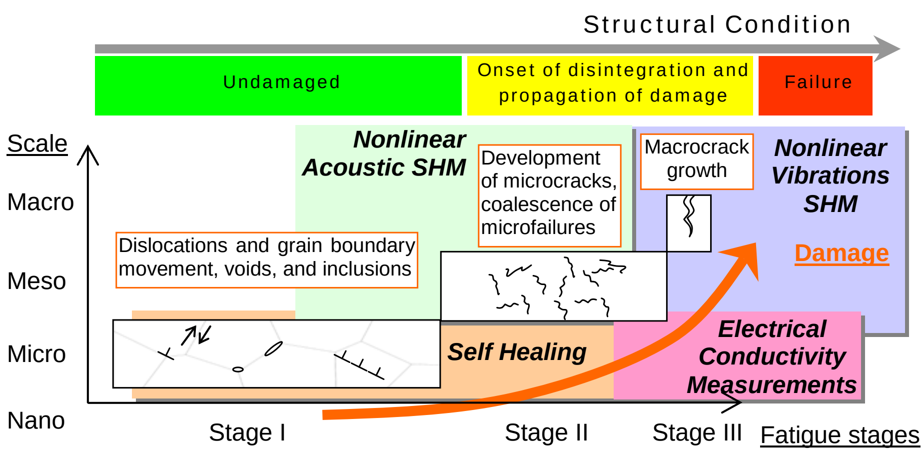

Figure 1 Damage accumulation in a structural system and the SHM methodologies associated with particular damage scales.

Development of the aforementioned SHM technologies combined with self-repairing materials concepts would contribute to economic and social benefits by enabling condition-based maintenance of aged and new aerospace structures and by prevention of catastrophic failures and loss of human lives. Our research efforts will be coordinated with the NASA MSFC materials science and structural dynamics teams led by Dr. Benjamin Penn and with the LANL structural health monitoring group led by Dr. Charles Farrar. The proposed project also will benefit the State-funded aerospace engineering (undergraduate and graduate) programs in New Mexico.

Objectives

- Develop a methodology for in-situ health monitoring and damage detection of aerospace structures using low frequency vibration and electrical conductivity measurements combined with high frequency nonlinear acoustic wave interrogation.

- Develop self-repairing materials for aerospace structures subjected to accumulated damage and use the proposed SHM methods to monitor the self-healing process.
- Contribute to and strengthen New Mexico aerospace engineering programs at NMSU and NMT and use the aerospace programs as vehicles to interest New Mexico K-12 students in STEM disciplines.
- Establish solid research expertise in the proposed technical areas in preparation for obtaining follow-up research funding.
- Develop nationally competitive research programs in the proposed and related areas in order to support the developing Aerospace Engineering MS and PhD programs at NMSU.

Expected significance

- Enabling condition-based maintenance of aerospace structures such as aircraft, launch vehicles, space vehicles and their critical components.
- Development of methods of combining various measurement techniques to recover information about various types of accumulate microstructural defects.
- Starting an interdisciplinary program which brings together expertise in micromechanics, vibrations and non-linear dynamics, materials science, and sensors array technology and controls to solve problems of great importance to NASA.
- Collaboration by five PIs from two research universities in close geographic proximity in a new NASA EPSCoR state which recently started a new aerospace engineering program.

Relation to Previous and Current Research

Summarized in this section are relevant research results obtained by the proposers and by others. These are organized into the four areas listed on page 2: 1) Combined joint/material nonlinear vibration-based methodology for low frequency SHM; 2) Development of cross property connections (electrical conductivity measurements) to determine bulk material properties for SHM; 3) High frequency SHM via nonlinear acoustics; and 4) Self-healing systems (SHS) of materials.

1) <u>Combined joint/material nonlinear vibration-based methodology for low frequency SHM</u>

The focus in the SHM community has been chiefly concerned with the identification of internal damage in structures on either a microscopic or macroscopic scale, with little attention for the integration of multi-scale damage detection techniques or the effects of non-ideal joints and boundaries. Most of the previous work on joints has been concerned with modeling and not on SHM and parameter identification. In contrast, the proposed research in SHM of self-healing structures will obtain and correlate damage information at multiple scales and will utilize existing joint damage models and non-ideal boundary conditions for identification of key damage parameters such as crack size, location, and density. The measurements of vibration frequencies and mode shapes contain combined information on macroscopic fatigue cracks in the internal structure and damage in the joints. That the vibration frequencies and mode shapes of cracked structures can be useful for an on-line detection of cracks is well-known (Imam, et al., 1989; Christides and Barr, 1984; Shen and Pierre, 1990; Yuen, 1985; Shen and Taylor, 1991). The fatigue crack models usually fall into two categories: 1) open crack (linear) models and 2) breathing crack (nonlinear) models. The breathing crack model takes into account the opening and closing of an elastic crack such that the motion of the beam alternates between two separate linear regions (i.e. with the crack open or closed) with two characteristic stiffness values (Cheng, et al., 1999). The dependence of natural vibration frequencies on the bilinear behavior of cracked structures was studied by Luo and Wu (2006) and Chati et al. (1997). The results from these studies indicate that a SHM method for crack detection should account for breathing cracks and must therefore take into account the nonlinear dynamics of this process.

There are three dynamic mechanisms that are regularly discussed in connection with jointed structures (Bergman and Segalman, 2007). The first mechanism called *slip* is that where large shear forces act across a joined section and a limited region of the section breaks free from the hold of friction and slides. Sliding in this newly freed region is called *micro-slip* if it occurs within a limited region; otherwise it is *macro-slip*. The second mechanism is *slap*. As a joint undergoes repeated loads, relative motion within that joint can cause sections to come into collision. The physics of vibro-impact are of paramount importance here. Unlike slip which is primarily concerned with energy loss, the main result in slap is to cause energy to be shifted away from the lower frequencies to the higher frequency range. The third mechanism involves the transmission and reflection of elastic waves at the joint. Most previous efforts in joint mechanics have utilized these mechanisms for modeling purposes only. For instance, the slapping process can be modeled using various spring-damper arrangements which couple the motions of neighboring masses only under certain conditions. Various compliant impact models include the Kelvin-Voigt (K-V), Maxwell, and other linear viscoelastic models (Hunt and Crossley, 1975; Herbert and McWhannell, 1977; Khulief and Shabana, 1987; Luo and Hanagud, 1998; Mills and Nguyen, 1992; Butcher and Segalman, 2000), as well as those based on nonlinear and fractional viscoelasticity. Our intent is to utilize the models which provide a more realistic description of the local structural deformation for the purpose of SHM through a combined measurement of frequency shift and energy dissipation due to the damaged joint.

2) <u>Development of cross property correlations (electrical conductivity measurements) to determine bulk material properties for SHM</u>

The use of electrical conductivity cross-property connections for SHM has, to the best of our knowledge, not been done. In order to apply cross property connections to damaged materials, it is necessary that the theoretical connections utilized take into account the types of material defects that may occur in practice, including anisotropy. The very possibility of such connections – that cover anisotropic cases – is far from obvious: not only are the field equations of conductivity and elasticity different, but the tensors characterizing these properties are of different ranks (2^{nd} rank conductivity tensor *vs* 4^{th} rank elasticity tensor).

The possibility of obtaining cross-property connections has been discussed in the literature for the last two decades. Aside from empirical connections of a curve-fitting nature (see, for example, the work of Kim *et al*, 2005, for metals), the work has focused mainly on establishing cross-property *bounds*, starting with works of Milton (1984) and Berryman and Milton (1988). However, bounding techniques have several limitations that make their application to materials of interest difficult. One of the limitations is that overall isotropy is assumed, whereas fatigued metals may have anisotropic microstructures.

Recently, explicit elasticity-conductivity connections have been derived by Sevostianov and Kachanov (2002). Aside from having an explicit form, that facilitates their applications to materials science, the results apply to anisotropic microstructures. For example, for *cracks* of arbitrary orientation distribution (general anisotropic case), the cross-property connection takes the form

$$\frac{E_i - E_0}{E_i} = 2\left(1-\nu_0^2\right)\frac{k_i - k_0}{k_i}$$

(E_i, k_i are the effective Young's modulus and the effective conductivity of a cracked material in a certain direction x_i and E_0, ν_0 and k_0 are the bulk material constants). This connection enables determination of the loss of stiffness due to microcracks from the changes in the effective conductivity.

3) High frequency Nonlinear Acoustics SHM

Over the past decade, considerable progress has been achieved in both fundamental and applied research on utilizing elastic wave propagation for SHM (Sohn, *et al*., (2003), Ihn and Chang (2004), Raghavan and Cesnik, (2005)). It has been shown that this approach allows for detection and location of structural damage ranging from delaminations and disbonds to small cracks (Lemistre *et al*., (2000), Guirgiutiu *et al*., (2003), Matt *et al*., (2005), Mal, *et al*., (2003). However, according to theoretical considerations (Bray and Stanley, 1997), detectability of structural damage in the elastic wave propagation techniques is sensitive to the wavelength of the transmitted/received elastic wave. On one hand, very small defects may not be resolved adequately if relatively low frequencies are employed. On the other hand, high frequency ultrasonic waves may attenuate rapidly, imposing limitations on the effective detection range. In complex structural components, misinterpretation of the test results is possible because the damage and the structural feature (a hole, notch, etc.) could reflect the same amount of acoustic energy.

One approach of addressing the small-scale damage and misinterpretation issues is to explore the nonlinear nature of the structural damage at high frequencies. Correlation between acoustic nonlinearity and material damage has been known for over forty years (Beyer, 1974). This work was pioneered by Mason (1960) in direct connection with studying physical properties of solids. Generation of ultrasonic second and third harmonics due to the micro-scale damage (dislocations) was discussed by Hikata, Elbaum, and Sewel (1966) in their classical papers. Since then, many authors have contributed to this subject. Examples include the work of Breazile (1984), Cantrell and Yost (2001), Nagy (1998), Van Den Abeele *et al*. (2001), Kim *et al*., (2004). Recent results on the use of the nonlinear acoustic approach for assessment of degradation in aerospace materials were reported by Frouin *et al*. (2000), Na *et al*. (2003), Donskoy *et al*., (2006), Zagrai *et al*. (2006a). The LANL group headed by Johnson uncovered an anomalously high mesoscopic nonlinearity (Guyer and Johnson, 1999), that, in the material with structural damage, may by orders of magnitude exceed the "classic" elastic nonlinearity. Although there is a considerable volume of work on application of the principles of the nonlinear wave propagation in NDE, realization of this methodology in the SHM context has been limited (Zagrai *et al*. 2006b). Only recently, the nonlinear methods became an active discussion topic in the SHM community (LANL, 2006). The development in this field is currently dominated by the nonlinear SHM methodologies exploring structural dynamics at relatively low frequencies (Doebling et al., 1996; Todd, *et al*., 2004, Adams and Nataraju, 2002, Epureanu *et al*., 2005). Although low frequency methods may yield a cost effective solution for assessment of overall structural health, their damage localization capabilities and sensitivity to the small-scale damage are limited. Therefore, we propose to couple the nonlinear ultrasonics technique with global nonlinear vibration methods to obtain a cumulative, multi-scale and complete picture of the structural health.

4) Self- Healing Systems (SHS) of Materials

The idea of engineering synthetic substances that are capable of self-repairing and adaptation to changing environments came to the scientific world many years ago. The concepts of structural polymeric materials with the ability to autonomically heal cracks were developed only recently (see, for example, White et al., 2001). According to these concepts, the material incorporates a microencapsulated healing agent that is released upon crack intrusion. Polymerization of the healing agent is then triggered by contact with an embedded catalyst, bonding the crack face. The proposed concept has disadvantages, such as high concentration of embedded capsules, weaker mechanical properties of the new material, and non-compatibility of healing and matrix materials.

Another interesting self-healing system is based on utilization of the electrohydrodynamic coagulation ability of particles to close a defect in materials (see, for example, Trau et al., 1997). An electric field is applied and a colloidal dispersion of polystyrene or silica particles is used to repair defects that occur in the material when high stress occurs. When a defect occurs in the insulating coating, the metal underneath is exposed to create high current density at the damaged site, causing colloidal particles to coagulate around the defect. The disadvantage of this technology is related to difficulties to detect the cracks and damages at the initial stages. Currently no technology is known for self-healing in metals and metal-based composites. The difficulties are high temperature and pressure during manufacturing processes of metallic parts (casting, forging, rolling, stamping, etc.). However, incorporation of the healing agent must be accomplished without premature damage during the manufacturing processes.

Technical Approach and Methodology

This section describing the proposed research contains five sections: four sections that describe the four methodologies listed on page 2, and a fifth section that defines how the four methodologies are to be combined into an integrated SHM/SHS strategy.

1) Vibration-based detection of fatigue cracks and damaged joints

For bilinear breathing cracks Butcher (1999) has derived a result for the equivalent linear stiffness k_{eq} at the location of a crack. The parameter k_{eq} is a function of the frequencies in the two linear sub-regions, the crack geometry, and the vibration amplitude. Butcher's approximate approach is well suited to detection of cracks via nonlinear vibration measurement, because the equivalent linear stiffness is generally applicable and can be used to obtain an equivalent linear model whose frequencies closely approximate those of the nonlinear structure even in the case where the crack has some non-vanishing gap (clearance), as well as in the case of multiple cracks. Other recent approaches to crack and damage detection such as modal filtering, statistical approaches, and use of the residual force vector (Bahlous et al., 2007; Lam et al., 2007; Yang and Liu, 2007) will be combined with the above method. The outcome will be a new analysis technique that will enable crack detection through vibration monitoring.

In order to effectively utilize the frequency effects of slap in non-ideal joints in vibration-based SHM, we propose to use various compliant boundary constraints which can incorporate a range of natural frequencies between known solutions for standard boundary conditions. For example, the frequencies of a beam with compliant non-ideal boundaries (e.g. spring-loaded) can encompass values from the lowest (i.e. for free ends) to the highest (i.e. for fixed ends) as in Fig. 2. This model can account for compliant boundaries and for nonlinear conditions such as deadzone or backlash. Such boundaries are characterized by alternate contact and separation from some compliant surface. We propose to approximate the frequencies of periodic mono-coupled systems with deadzone or backlash boundaries as a function of the nonlinear boundary parameters using pass- and stop-bands (Mead, 1975), and using interpolation between known boundary solutions. The resulting approximations yield useful results over the entire range between the known solutions, and this breadth is desirable from the SHM standpoint.

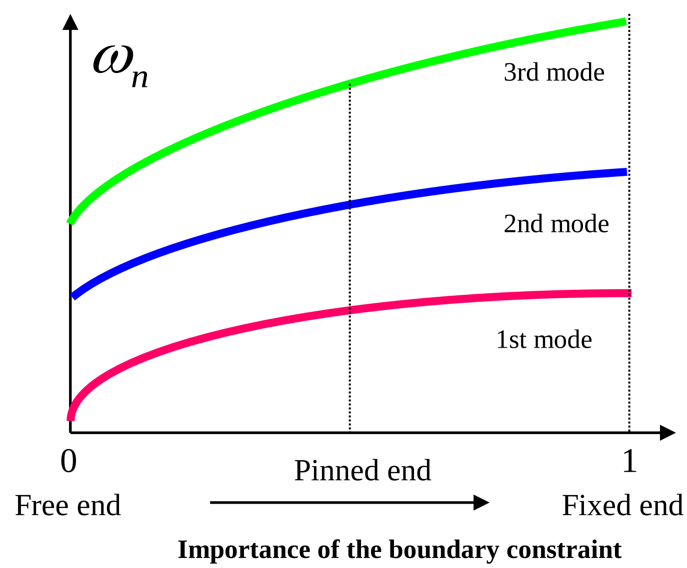

Fig. 2 Schematic of a beam's modal frequencies as a function of the boundary condition

The results obtained from the procedures proposed above should enable the sizes, depth and location of cracks as well as the deviation from ideality of the boundary conditions to be identified in SHM. In addition, the bilinear breathing crack model together with the pass- and stop-band model of spatially periodic structures will enable construction of accurate amplitude-dependent nonlinear and approximate linear models for use in finite element model updating of the damaged structure. Such models typically have large dimension and must be reduced in size. Therefore, some recent order reduction methodologies including principal orthogonal decomposition (POD) and others (Butcher and Lu, 2007; Segalman, 2007; Kumar and Burton, 2007; Kerschen et al., 2005) for systems with localized nonlinearities will be employed in order to accurately represent the damaged structure with a low-dimensional model. Low order models will be essential in the future if real time, on-line SHM is to be realized.

2) <u>Cross Property Connections</u>

The proposed work builds on research in micromechanics of materials with defects and cross-property connections for such materials published by Sevostianov and co-workers in the past 4-5 years (Sevostianov, 2003; Sevostianov and Kachanov, 2002; Sevostianov, et al, 2002; Kachanov, et al, 2001, 2005). Cross-property connjections should reflect those microstructural features that have a dominant effect on the elastic and conductive properties. This means identification of the *proper microstructural parameters*, in whose terms the said properties are to be expressed. The parameters must represent individual defects in accordance with their actual contributions to the properties, with their shapes and orientations taken into account. For example, for circular cracks of non-random orientations, the (2nd rank) crack density tensor is defined by

$$\boldsymbol{\alpha} = \frac{1}{V}\sum\left(l^3\boldsymbol{nn}\right)^{(k)}$$

where $l^{(k)}$ is radius of the kth microcrack and $\boldsymbol{n}^{(k)}$ is a unit normal to kth microcrack.

The proper microstructural parameters describe the overall anisotropy. Proper quantitative characterization of rather complex microstructures may actually be given by a small number of parameters. For example, a preferential orientation of circular cracks with a scatter is characterized by two components $\alpha_{11} = \alpha_{22}$ and α_{33} of the crack density tensor, that reflect, in an integral way, both the extent of the scatter and the crack density. We plan to develop results of this kind for non-planar crack geometries. Moreover, proper microstructural parameters imply explicit elasticity-conductivity connections in those cases when the mentioned parameters for these two properties are sufficiently similar (Sevostianov and Kachanov, 2002).

The shapes of microcracks in metals and microgeometry of the porous space in foams may be quite complex. A difficult problem is to find an equivalent distribution of ellipsoidal inhomogeneities in the context of the *elastic* properties. Because the elasticity tensor is of 4th rank, an arbitrary pore/crack cannot be replaced by an equivalent ellipsoidal crack. The basic problem emerges of finding the simplest "standard" shapes, to which a pore of an *arbitrary* shape can be reduced. We note that this problem is of fundamental interest for broader material science applications that are not limited to metals.

The challenge is to distinguish the *"irregularity factors"* of primary importance that produce substantial effects on of the overall elasticity/property, from factors of minor importance, and to develop sufficiently simple *quantitative characterization* of these primary factors. Such analyses will combine the theoretical methods based on bounding approaches (such as Hill's comparison theorem) and computational studies. Some preliminary results in this direction are summarized in Figure 3 below.

The cross-property connections have been derived under the assumption that *interactions* between defects (elastic and conductive ones) can be neglected. Strictly speaking, this limits their use to relatively low defect concentrations. This is too limiting for application to SHM; for example, density fatigue microcracks may be substantial (Wen and Keer, 2002). Although preliminary experimental data indicate that the cross-property connections continue to hold at non-small defect densities (Sevostianov et al 2002a), theoretical work is needed to put these connections on solid footing.

The outcome of this research will be twofold: 1) an independent method to determine the change in bulk material properties due to damage – this information will be used in the vibration and acoustic SHM methodologies; and 2) research to establish direct connections between measured or inferred cross-property connection parameters and damage in materials – this would add a fundamentally new methodology to SHM.

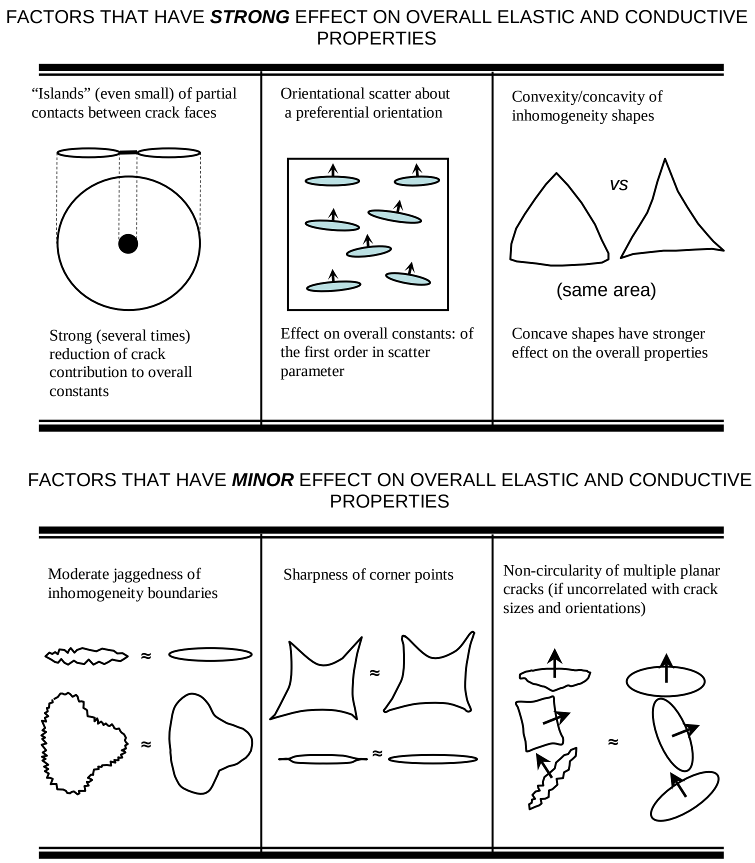

Figure 3: Effect of various "irregularity factors" on the overall elastic and conductive properties

3) <u>Embedded Nonlinear Acoustics</u>

A harmonic acoustic wave propagating in a nonlinear medium is distorted, leading to a number of interesting phenomena including shock formation, generation of multiple harmonics and nonlinear interaction with structural inhomogeneities. A one-dimensional wave equation in the second order nonlinear approximation shows that displacement of the elastic wave is dependent not only on linear elastic properties of the medium, i.e. sound speed $c_0 = (E / \rho)^{1/2}$, where E is an elastic modulus and ρ is a mass density, but also on the nonlinear parameter of the medium β.

$$\frac{\partial^2 u}{\partial t^2} - c_0^2 \cdot \frac{\partial^2 u}{\partial x^2} = -2\beta c_0^2 \cdot \frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial x^2}$$

This parameter, in general, includes spatial dependence and can be physically attributed to the nonlinear processes at various scales: lattice anharmonicity at the atomic scale, β_A, and dynamics of dislocations, grain boundary separations, formation of cracks at micro, meso, and macro scales, β_M (Van Den Abeele *et al.*, 1997, 2000), so that $\beta = \beta_A + \beta_M$. Therefore, *measurements of β could potentially provide information on the nonlinear processes associated with damage*.

To augment the nonlinear vibration SHM methodologies that employ relatively low frequencies, we propose a high frequency SHM technique that is based on the nonlinear interaction of the propagating elastic waves at the site of an incipient damage. The technique utilizes a complex multi-component excitation signal facilitating the amplitude-phase modulation of the elastic wave. The result of the quadratic nonlinear interaction of the elastic waves due to damage-induced structural nonlinearity is manifested at the combination (modulation) frequencies, $\omega_{\pm}=\omega_0\pm\omega_1$, as presented in Figure 4. These spectral components contribute into the nonlinear acoustic signal propagating through the damaged structure.

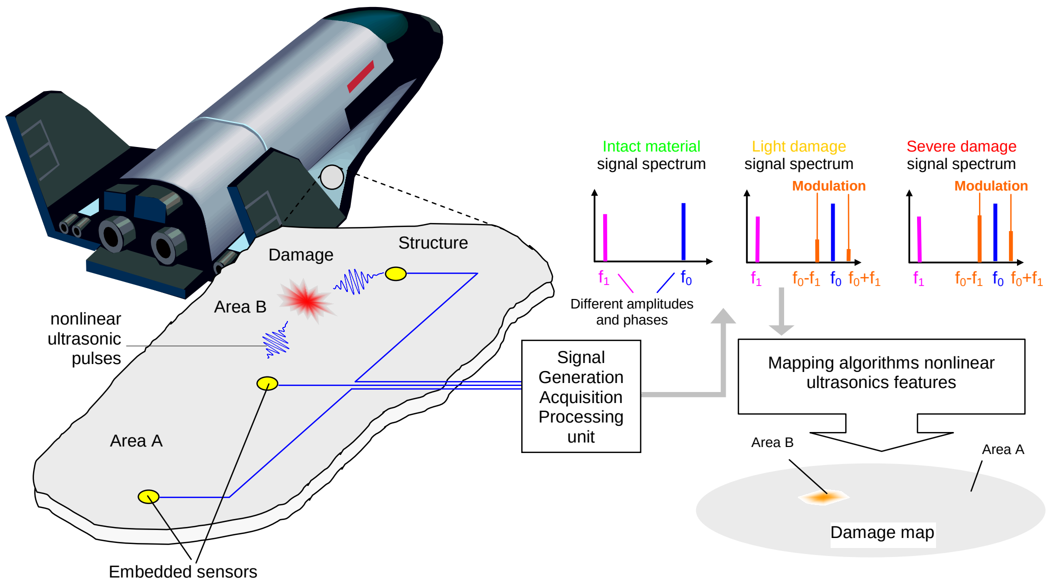

Figure 4 The embedded nonlinear ultrasonics concept.

Material fatigue, disintegrations in the form of cracks and disbonds noticeably affect the nonlinear acoustic parameter and, therefore, affect behavior of the spectral components at the combination frequencies $\omega_{\pm}$.

It should be noted that separately the amplitude modulation and the phase modulation techniques have been considered in NDE applications (Donskoy *et al.*, 2001, Rokhlin *et al.*, 2004, Jacob, *et al.*, 2003). However, both the amplitude modulation and the phase modulation of the elastic waves are only particular cases of a more general amplitude-phase modulation that we plan to explore in the proposed embedded SHM methodology. One of the challenges of the proposed research efforts is to realize the nonlinear ultrasonics in the embedded format. This will require development of new thin wafer embeddable sensors/transducers, investigation of the transducers-governed performance characteristics of the methods, studying detrimental influences of nonlinearities from other sources such as bonding, instrumentation, etc.

One of the emphases of this proposal is early and multi-scale damage assessment. We will explore capabilities of the embedded nonlinear ultrasonics in detection of fatigue damage. Previous studies (Zagrai *et al.*, 2006b) have indicated that in the NDE format, use of non-embeddable transducers combined with bulk wave propagation, renders detection of structural fatigue possible, in principle. However, manifestation of acoustic nonlinearity in thin-walled structures during fatigue still awaits a detailed investigation. Our goal is to conduct the embeddable nonlinear ultrasonic guided wave monitoring of structural fatigue and to correlate the results with electrical conductivity and nonlinear dynamics measurements. Availability of the real-time nonlinear ultrasonic data on structural deterioration will open new opportunities in prognosis and will facilitate improvements in structural maintenance and safety.

4) Self-Healing Systems (SHS) of materials

The research team will target a revolutionary technology for self-healing concepts in metals, alloys and plastic composites, which can lead to significantly increased safety of civil and military structures, aerospace and ground vehicles. As mentioned above, no technology is known for self-healing in metals and metal based composites. Several concepts will be developed and realized for self healing in metals. In one of the concepts a self-healing is assumed to be achieved by incorporating a microencapsulated healing agent of complex composition and a catalyst within the metal matrix composite manufactured via powder metallurgy process. Microcapsules will be filled by the same bonding agent used in sintering processes. A propagating crack will burst the microcapsules. The healing agent released into the crack will contact the catalyst particles. Bakhtiyarov and Overfelt (1997-2002) demonstrated an exothermic character of most two-part binding systems. These findings will be utilized in another self-healing concept of metals, alloys and metal-based composites. CFD simulations will be conducted to model a quasi-static bubble formation from the burst microcapsules into the crack space. In terms of the candidate fillers, a self-healing system (SHS) of exothermic reactions, such as Ti and C for example, would be initiated by the heat generated from the approaching crack and the compound formed would fill the cavity and thus cure the crack and avoid failure in the system. These components have to be chosen from SHS systems that are compatible with the material to be cured. The presence of microcapsules containing the SHS components would enhance toughness in the material, with the interfaces generated, and the new alloy (compound) formation would be the requisite cure to the crack.

Two concepts will be developed for thin coatings. In the first concept, the research team will develop chemically, thermally and mechanically stable conducting coating materials capable to detect the damaged (cracked) area in the material's surface. The signal on the damage will be sent to the external field generator (thermal, electrical, magnetic, etc.) to initiate a self-healing process by coalescing field active particles (initially introduced to the matrix) around the defect. Another self-healing concept will be based on the Diels-Alder phenomenon. The Diels-Alder reaction is essentially a cycloaddition reaction in which an alkene adds to a 1,3-diene to form a 6-membered ring. Previously, this reaction was studied with nitrile groups and methoxy groups on both reactants in varying positions. The reaction is synthetically applicable for self-healing of ceramic and plastic materials, due to the formation of cyclic products. Over the past decade, analytical chemists demonstrated an interest in studying the transition states and energies of activation and entropies. Diels-Alder phenomenon is a unique phenomenon able to heal fractures. However, there still are many uncertainties in the mechanism of this phenomenon. The proposed studies will involve the rates of reaction and the mechanism of the self-healing.

The research team will develop new classes of nanoencapsulated systems for binders. The healing agent and the catalyst will be encapsulated within double-walled nanotubes. The double-walled nanotubes have a coaxial structure, containing two concentric cylinders. They have higher thermal and chemical stability than single-walled nanotubes and spherical capsules. By applying the catalytic chemical vapor deposition process, the core and the annular spaces of the double-walled nanotubes will be filled by the healing agent and the catalyst, respectively. A crack within the composite matrix will rupture embedded nanotubes. The healing agent and the catalyst will be released into the crack via capillary effects. Upon the contact of the healing agent with the catalyst, a polymerization will be generated, and the crack will be filled. The advantages of using double-walled nanotubes are: (i) a nanosizing of the capsules will allow to increase the surface area more than 1,000 times compared to the spherical microcapsules at the same mass concentration; (ii) the material of the nanotubes can be selected to be compatible with both curing agents and the matrix composite, and this will eliminate the undesirable interface effects; (iii) the healing agent and the catalyst will be released simultaneously; (iv) the embedded double-walled nanotubes will increase thermal, mechanical and chemical stability of the matrix composite; (v) the continuous shape of the capsules will increase probability of their rupturing by the propagated crack.

5) Integration of multi-scale SHM and SHS methodologies

The three SHM techniques discussed in this proposal will be closely integrated in two important ways. First, the techniques will yield information concerning damage in the internal structure at three different scales: 1) vibration-based SHM to determine the sizes and locations of macroscopic fatigue cracks, 2) electrical conductivity measurements to determine changes in bulk material properties, and 3) acoustic wave propagation to determine microscopic crack densities. This information will be integrated to form a complete multi-scale model of the structure in which the effects of damage at any scale may be extracted. One popular approach which will be investigated for this purpose is the use of fractal mathematics. Fractals are functions which describe topographies with great detail at all length scales, and could be used to approximate multi-scale damage effects. Second, because the vibration-based SHM measurements contain combined information on the structure's material and joint damage, these aspects of the structure must be separated to yield a joint damage model which is distinct from the material damage model. Here, the additional information on the material damage obtained through the other measurement techniques will help to separate out the effects of the joints from the material damage. During the first year of the project the research team will design candidate experiments intended to be sufficiently broad to allow both individual and integrated SHM methodologies described in this proposal to be tested and validated experimentally for multi-scale damage and for joint/material damages occurring together. During years 2 and 3 the validating experiments will be conducted. It is anticipated that a comprehensive experimental validation program will need to be carried out as a follow-on project.

For SHS/SHM integration, including experimental work, the proposed SHM systems (nonlinear ultrasonics, four-point collinear probe resistivity, etc.) will detect defects by continuous scanning of the coated surfaces. The signals from detection systems will initiate activation of the self-repairing particles and appropriate local environmental conditions, such as temperature, pressure, humidity, etc. One of the challenges of the self-repairing materials technology is to embed micro sensors into the developed matrix so one can predict failure with confidence. Usually, sensors are positioned randomly, organizing themselves into a network with no maintenance. However, in order to maintain the strength and other properties of the self healing material, sensors must be embedded in desired locations where the probability of failure is high. Therefore, a Rapid Prototyping (3D Printing) technology will be the most suitable manufacturing technique to introduce the "healing" agents (capsules) into the matrix material and imbed micro sensors during the 3D printing process. The first test samples are suggested to be manufactured using a Rapid Prototyping technology. A rapid prototyping machine reads in data from a CAD drawing and lays down successive layers of liquid or powder material. It builds up the prototype model from a series of cross sections. The layers are glued together automatically to produce the desired shape. This technology is applicable for a wide variety of materials (polymers, thermoplastics metals, ceramic powders, etc.), high temperature and high pressure conditions are not required.

Impact of the proposed work to the state of knowledge in the field

- Methodology incorporating nonlinear crack and joint modeling to complement material damage modeling will be a significant advance in the state of the art. For many aerospace structures the possibility of joint/connection damage cannot be ignored.
- Nonlinear acoustic SHM using embedded sensors promises to be an excellent method for local, small-scale damage detection. Accompanying advances in applications of signal processing to detect small nonlinear effects in the acoustic responses will be valuable.
- The use of electrical conductivity measurements and cross-property connections to provide more information is a new addition to the field of SHM. Furthermore, in the future the methods may lead to new SHM approaches, as yet unknown, whereby electrical conductivity measurements and/or cross-property connection parameters can be related directly to structural damage.
- The possibility to develop self-healing materials in such a way that failure is prevented and material toughness is maintained would be of significant value in aerospace applications. It is anticipated that the proposed research in this area will provide the seeds for significant future work in this area.
- The proposed framework, in which multi-scale damage and combined joint/material damage are considered through integration of the aforementioned methodologies, will be valuable in the future, as SHM matures to the point where the development of real time, self-monitoring and self-healing materials becomes routine.

Relevance to NASA programs (incl. relevant NASA research programs; include relevance to specific objectives of program)

The proposed research is directly applicable to the following research programs at NASA Mission Directorates:

ARMD
Aircraft Aging and Durability Detection
Aircraft Aging and Durability Mitigation
Aircraft Aging and Durability Prediction
Airframe Health Management
Optical Instrumentation and NDE Technology
Structures and Materials

ESMD
Advanced Materials

In addition, twelve research programs at four NASA Centers (Langley, Marshall, Glenn, and Dryden) have been identified as directly related to the proposed research.

Management and Evaluation

Personnel

- Principal Investigator - Patricia C. Hynes, Director of the New Mexico NASA EPSCoR Program and Director of New Mexico Space Grant Consortium.
- Co-Investigator, Sayavur Bakhtiarov, ME Chair, New Mexico Tech
- Co-Investigator, Thomas Burton, ME Head and Professor, NMSU

- Co-Investigator, Eric Butcher, Assoc. Prof. of ME, NMSU
- Co-Investigator, Igor Sevostianov, Assoc. Prof. of ME, NMSU
- Co-Investigator, Andrei Zagrai, Asst. Prof. of ME, NMSU
- Research Assistants to be identified
- Graduate Students supported by this research effort will be U.S. citizens in an effort to build the technical workforce prepared to work for NASA and its contractors. New Mexico NASA EPSCoR is committed to supporting diversity and will encourage female, minorities and persons with disabilities to actively participate in the program.

Research Program Management

The technical aspects of the proposed research will be performed by the five co-PI's, with participation as follows (lead investigators underlined will manage the listed technical areas):

- Nonlinear vibration based methodology Butcher, Burton, Zagrai
- Cross-property connections: Sevostianov, Butcher, Bakhtiarov
- Nonlinear acoustic SHM: Zagrai, Burton, Butcher
- Self-healing systems (SHS): Bakhtiarov, Zagrai, Sevostianov
- Integration of Multi-Scale SHM/SHS methodologies: Burton, Bakhtiarov, Butcher, Sevostianov, Zagrai

New Mexico EPSCoR will be managed through the New Mexico EPSCoR/Space Grant lead office at New Mexico State University. Dr. Patricia C. Hynes, Director of New Mexico Space Grant, will also serve as the Director of NASA EPSCoR and will be responsible for the day-to-day management of the NASA EPSCoR program, including interactions among collaborating institutions, NASA Field Centers, and space and aerospace related industry**.** The NM EPSCoR Director will work with the State of New Mexico EPSCoR Committee to facilitate interactions and coordination between these organizations. The NM EPSCoR Director will work closely with the Technical Advisory Committee (TAC) to align our research focus to meet NASA and New Mexico research priorities. The EPSCoR office will be responsible for contract requirements including budgeting and reporting requirements. NASA EPSCoR office will also organize annual meetings for New Mexico faculty to facilitate research collaborations among colleges and universities.

Program Evaluation – Researchers – add something on your specific research goals as appropriate (done in main body)

Evaluation is a key consideration not only in the demonstration of effectiveness of the program, but also in continuous improvement and program refinement. New Mexico EPSCoR Director Dr. Patricia Hynes has conducted extensive activities in educational assessment. She will design and implement the evaluation plan. Evaluation data will be collected from researchers each year as part of their report to NASA EPSCoR. The evaluation will allow us to monitor our progress and document benchmarks toward achievement of program goals and objectives.

The evaluation will be both formative and summative. Formative evaluation will include an annual assessment of the proposed research metrics. Formative evaluation results will be brought to the NASA EPSCoR Technical Advisory Committee (TAC) for feedback and strategies to increase program success. Annually, we will be looking for faculty and research areas which show promise for additional funding. Summative evaluation will include a comparison of pre-award and post-award data analysis.

Research faculty will involve undergraduate and graduate students in their research. This will not only contribute to workforce development in NASA research areas but encourage student retention. Students receiving $5,000 or more in support will be tracked through first employment. We will track students through the university registration systems, confirming students are still enrolled and succeeding in their STEM degrees.

The goals and their metrics for New Mexico EPSCoR are:

Goal #1: Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while assessing and leveraging the many existing core capabilities relative to NASA in the state.

Metric: Evidence of reordered New Mexico and/or institutional priorities
Metric: Evidence of how EPSCoR activities have furthered jurisdiction priorities.
Metric: Financial commitment from the jurisdiction, industry, and participating institutions

Goal #2: Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program in space and aerospace related science, technology, engineering and mathematics research.

Metric: Number of follow-on grant proposals submitted and/or funded.

Goal #3: Develop partnerships between NASA research assets and New Mexico academic institutions, federal laboratories, and industry.

Metric: Extent to which collaborations with New Mexico agencies, industry, research and academic institutions and with NASA have evolved.

Goal #4: Contribute to New Mexico's overall research infrastructure, science and technology capabilities, higher education, and/or economic development.

Metric: Number of articles submitted to and/or published in refereed journals
Metric: Number of talks, presentations or abstracts at professional meetings
Metric: Number of patents awarded
Metric: Number and gender/ethnicity of students participating in the program research. We will track student persistence through to degree completion and where they go after graduation.

Goal #5: Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) to improve the environment for science, mathematics, engineering, and technology education in New Mexico.

Metric: Increased number and quality of interactions between researchers and New Mexico Space Grant Consortium

Tracking of Program Progress

- the progress and potential towards achieving self-sufficiency beyond the award period of the research capabilities developed under this grant; The NMT/NMSU SHM/SHS collaboration will be able to expand its research to include NASA and the federal labs in New Mexico, leading to a large, self-sufficient research program at the two universities.

- the potential for the proposed research area to continue to grow in importance in aerospace fields in the future. (addressed in main body)

Continuity - Researchers – add something specific about your project here – how will your research continue? (addressed in timeline)

Through their participation in this research students are prepared for employment in disciplines needed to achieve NASA's mission and strategic goals. We will encourage participation from New Mexico students enrolled in other NASA sponsored programs, such as USRP, GSRP, or ESMD. Through this research and internships and fellowships students become participants in NASA's Vision for Space Exploration and NASA's science and aeronautics research, and acquire sufficient mastery of knowledge for employment with NASA and its contractors.

EPSCoR funding provides researchers equipment and material necessary to advance this research area in the state. This funding supports faculty publications, increasing their eligibility for non-EPSCoR funding, and bringing the research team to a level of national competitiveness.

Timeline and milestones

Year 1: Conduct theoretical/modeling/simulation research intended to reveal the most promising (and the least promising) specific lines of attack in each of the individual research areas and in the methodology for integration of the SHM and SHS approaches. Design an experiment that is sufficiently broad based that it will enable methodology validation to be accomplished.
Year 2: Continue the work on methodology development, with increased focus on integration of the individual research areas into the overall SHM/SHS methodology. Conduct the experimental research planned in year 1, with modifications as needed, depending on outcomes.
Year 3: Complete sufficient experimental work to enable individual and integrated methodologies to be validated. The outcome of the proposed research will be an integrated SHM/SHS methodology, with some experimental validation. It is anticipated that additional experimental research will need to be done in follow-on projects. It is also anticipated that follow-on research in the theoretical methodologies will be needed, depending on the outcomes of the proposed research.

Collaborators (persons/groups listed have agreed to be collaborators on the proposed project).

Dr. Benjamin Penn, Polymer Scientist, NASA Marshall Space Flight Center, Org. EV 43 – Advanced Materials and Sensors for Space Exploration, Huntsville, AL (256-544-7809). Area of interests: self-healing materials and sensors for space exploration.

Dr. Shandor (Alex) L. Lehoczky, Technical Specialist, Microgravity Science and Application Department, SD 46, NASA Marshall Space Flight Center, Huntsville, AL 35812 (256-544-7758). Areas of interest: Self Healing Materials, Solid State Physics, Materials Science, Properties of Materials, Electronics Materials, Microgravity.

Dr. John Lekki, Optical Systems Research Engine,NASA Glenn Research Center, MS 77-121000 Brookpark Rd., Brook Park, Ohio 44135 (216)433-5650. Areas of interest: optical systems, structural health monitoring

Dr. Chuck Farrar and his group at LANL (Matt Bement, Kevin Farinholt, Gyuhae Park) – MS T-001, LANL, Los Alamos, NM, 87545 (505-663-5330). Areas of interest: SHM, sensing, *in situ* measurements, signal processing, feature extraction.

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a) Professional Preparation

Birmingham University, UK	Mech. Engineering	ScD 1992
Institute of Thermophysics, Russia	Mech. Engineering	PhD 1978
State Oil Academy, Baku	Mech. Engineering	MSc 1974
Institute of Oil and Chemistry, Baku	Petrol. Engineering	BSc 1972

b) Appointments

New Mexico Tech	Associate Professor, Dept. Chair	since 1/05
Auburn University, AL	Research Professor	2/95 – 1/05
Azerbaijan Oil Academy	Professor, Dept. Chair	5/78 – 2/95
Academy of Sciences, Baku	Research Fellow Professor	8/74 - 1/75

c) Publications

Refereed Scholarly Journals – 95
Books and Chapters in Books – 24
Conference and Symposia Proceedings – 111
Professional Magazines – 5
Patents (existing and pending) – 11
Graduate Students supervised – 6 PhD, 15 MS

(i) Publications (5 publications closely related to the proposed project)

1. 1. S. I. Bakhtiyarov and R. A. Overfelt, 2006, “Improved Sand-Compaction Method for Lost-Foam Metal Casting”, **NASA Tech Brief**, MFS-31679-1.
2. N. Khidasheli, E. Kutelia, S. Bakhtiyarov, G. Beradze and K. Demirkiran, 2006, “Thermo-Mechanical and Isothermal Treatments Influence on the Wear of ADI during Dry Friction”, **Georgian Engineering News,** No. 4, pp. 25-34.
3. S. I. Bakhtiyarov, 2006, “Numerical Simulations and Experimental Study of Liquid Metal Flow around Sand Core”, **Journal of Fluids Engineering,** Vol. 128, pp. 541-547.
4. E. R. Kutelia, O. O. Tsurtsumia, B. G. Eristavi, H. Adanir and S. I. Bakhtiyarov, 2006, "Structure and Elemental Distribution in Beilby Layer on the Surface of Fe-Cr-Al-La Alloy", **Journal on Engineering and Technology,** Vol. 1, No. 4, pp. 61-71.
5. S. I. Bakhtiyarov, M. Dupac, R. A. Overfelt and S. G. Teodorescu, 2004, “On Electrical Conductivity Measurements of Molten Metals by Inductive Technique”, **Journal of Fluids Engineering,** Vol. 126, pp. 468-470.

(ii) Publications (5 other significant publications)

1. S. I. Bakhtiyarov and R. A. Overfelt, 2006, “Improved Probe for Evaluating Compaction of Mold Sand”, **NASA Tech Brief**, MFS-31678-1.
2. S. I. Bakhtiyarov, O. T. Inal, B. Guo, R. A. Overfelt, 2005, “A New Image Analysis Method for Shape Prediction of a Levitated Aspherical Droplet”, **Journal on Engineering and Technology,** Vol. 1, No. 1, pp. 67-73.
3. S. I. Bakhtiyarov, R. A. Overfelt and D. Wang, 2005, “Thermophysical Property Measurements on Mold Materials: Thermal Expansion and Density”, **International Journal of Thermophysics,** Vol. 26, No. 1, pp. 141-149.
4. S. I. Bakhtiyarov and R. A. Overfelt, 2004, “Effect of Porosity and Metallic Insertions on Electrical Resistivity of A2011 Aluminum Alloy”, **Materials Science and Technology**, Vol. 20, pp. 790-794.
5. A. J. Meir, P. G. Schmidt, S. I. Bakhtiyarov and R. A. Overfelt, 2004, “Numerical Simulation of Steady Liquid-Metal Flow in the Presence of a Static Magnetic Field”, Transaction of the ASME, **Journal of Applied Mechanics** Vol. 71, pp. 1-10.

d) Synergistic Activities

- Symposium coordinator and topic organizer of ASME International Mechanical Engineering Congress and Expositions, ASME Fluids Engineering Summer Meetings, AFS Congresses, since 1996
- Editor in Chief of the “International Journal of Manufacturing Science and Technology” (IJMS&T) and International Journal of Mechanics and Solids (IJM&S)
- Editorial Board Member of Journal of Mathematics Applied in Science and Technology (MAST), International Journal of Applied Engineering Research (IJAER), International Journal of Dynamics of Fluids (IJDF), Far-East Journal of Mathematics (FEJM)

Biographical Sketch - THOMAS D. BURTON

EDUCATION
PhD in Mechanical Engineering and Applied Mechanics, University of Pennsylvania, 1976
MS in Mechanical Engineering and Applied Mechanics, University of Pennsylvania, 1972
BS in Engineering (Major: Aero), California Institute of Technology, 1969

PROFESSIONAL EXPERIENCE

6/05 – present	Head, department of Mechanical Engineering, New Mexico State University, Las Cruces, New Mexico, 88003-8001
7/95-6/05	Chair (7/95 – 8/04) and Professor, Department of Mechanical Engineering, Texas Tech University, Lubbock, Texas 79409-1021.
6/97-present	Consultant, Los Alamos National Laboratory, Engineering Sciences and Applications – Weapons Research, Los Alamos, NM
8/91-10/92	Acting Department Chair, Mechanical and Materials Engineering Department, Washington State University, Pullman, WA 99164-2920.
1977-1988	Professor (1988-1995), Associate Professor (1982-88), Assistant Professor (1977-82), Department of Mechanical Engineering, Washington State University, Pullman, WA.
1969-1977	Engineer, General Electric Co., Missile and Space Division, Valley Forge, PA: 1975-77: Intelligence Programs Group, Space Sciences Lab; 1969-75: Flight Dynamics Group, Re-Entry and Environmental Systems Division.

Relevant Publications of Past 5 years

J. Kim and T. D. Burton, "Reduction of Nonlinear Structural Models Having Non-Smooth Nonlinearities, Proc. IMAC XX, pp. 324-330, Los Angeles, CA (2002).

J Kim and TD Burton, "Reduction of Structural Dynamics Models Having Nonlinear Damping," ASME 2003 DETC, 19th Biennial Conf. On Vibration and Noise, September 2-6, Chicago, IL (2003).

Burton, TD, "Numerical Calculation of Nonlinear Normal Modes in Structural Systems," *Nonlinear Dynamics*, to appear (2007).

J Kim and TD Burton, "Reduction of Structural Dynamics Models with Nonlinear Damping," *J. Vibration and Control* (in review).

N Kumar and TD Burton, "Use of Random Excitation to develop POD based reduced order models for nonlinear structural dynamics," Proc. ASME IDETC, Paper DETC2007/VIB-35539, Las Vegas, NV, September 4-7 (2007)

Other relevant publications

J-L Ding, J Pazhouh, SB Lin and TD Burton, "Damage Characterization by Vibration Test," *Scripta Metallurgica et Materialia*, **30**(7), 839-844 (1994)

T.D. Burton, C.R. Farrar, and S.W. Doebling, "Two Methods for Model Updating Using Damage Ritz Vectors," Proc. IMAC XVI, pp. 973-979, Santa Barbara (1998).

TD Burton and W Rhee, "On the Reduction of Nonlinear Structural Dynamics Models," *Journal of Vibration and Control*; **6**(4), pp. 531-556 (2000).

T. D. Burton, F. M. Hemez and W. Rhee, "A Combined Model Reduction/SVD Approach to Nonlinear Model Updating," Proc. IMAC XVIII, pp. 116-123, San Antonio (2000).

P Meekangvan, AA Barhorst, TD Burton, S Chatterjee, and L Schovanec, "Nonlinear Dynamical Model and response of Avian Cranial Kinesis," *J. Theoretical Biology*, **240**, 32-47 (2006).

Synergistic Activities
National President, Pi Tau Sigma (ME Honorary Society), 2003 – 2007.
Development of non-technical Senior Seminar for ME students for real-life preparation
Member (2000-2006), external review panels for ASCI code development projects in mechanics (Sandia NL and LANL)
Editorial Board member, *Journal of Vibration and Control*
Guest editor, 2 special issue of the journal *Nonlinear Dynamics*
Member, Organizing Committee, International Symposium for Personal Spaceflight (2005 – present)

Biographical Sketch - ERIC A. BUTCHER

Department of Mechanical Engineering
New Mexico State University, Las Cruces, NM 88003
Phone: 1-505-646-6179 Fax: 1-505-646-6111
E-mail: eab@nmsu.edu Website: http://me.nmsu.edu/faculty/eab.htm

Education

Ph.D. (Mechanical Engineering), 1997, Auburn University, Auburn, AL. Advisor: Prof. S. C. Sinha
M.S. (Mechanical Engineering), 1995, Auburn University, Auburn, AL. Advisor: Prof. S. C. Sinha
B.S. (Engineering Physics) with distinction, 1993, University of Oklahoma, Norman
B.M.A., 1991, University of Oklahoma, Norman

Post-Graduate Positions

2007-____: Associate Professor, Mechanical Engineering Dept., New Mexico State University
2003-2006: Associate Professor, Mechanical Engineering Dept., University of Alaska Fairbanks (tenured)
1998-2003: Assistant Professor, Mechanical Engineering Dept., University of Alaska Fairbanks
1997-1998: Postdoc/Technical Staff Member, Structural Dynamics and Vibration Control Department, Sandia National Laboratories, Albuquerque, NM. Supervisor: Dr. Daniel Segalman

Research Interests

Nonlinear dynamics, vibrations, controls, and mechanical design of systems and structures.

Awards

Inaugural holder of Chapman Endowed Professorship, Dept. of Mechanical Engineering, New Mexico St. Univ.

Synergistic Activities

Reviewer of papers submitted to: *J. Vibration & Acous.*, *Int'l J. Non-linear Mech.*, *Math. & Computer Modelling*, *J. Dyn. Sys., Meas.,& Control*, *J. Vibration &Control*, *Mechanism & Machine Theory*, *Nonlinear Dynamics*, *J. Computational and Nonlinear Dynamics*, *J. Sound & Vibration*, various conferences
Reviewer of proposals submitted to the National Science Foundation and the Army Research Office
Symposium organizer for ASME IDETC 2001, 2003, 2005, 2007; ICSV 2002, 2003
Outreach: Worked with elementary school students in Lego Robotics Competition

Publications

Dr. Butcher has authored **32 refereed journal papers, 29 refereed conference articles, and 10 conference abstracts**. A list of 8 relevant journal publications is given below:

1. Butcher, Eric A. and R. Lu, "Order Reduction of Structural Dynamic Systems with Static Piecewise Linear Nonlinearities," *Nonlinear Dynamics,* published online Jan. (2007).
2. Deshmukh, V., E. A. Butcher, and S. C. Sinha, "Order Reduction of Parametrically Excited Linear and Nonlinear Structural Systems," *J. Vibration and Acoustics* 128, 458-468 (2006).
3. Sinha, S. C., S. Redkar, V. Deshmukh, and E. A. Butcher, "Order Reduction of Parametrically Excited Systems: Techniques and Applications," *Nonlinear Dynamics* 41, 237-273 (2005).
4. Sinha, S. C., S. Redkar, and E. A. Butcher, "Order Reduction of Nonlinear Systems with Time-Periodic Coefficients Using Invariant Manifolds," *J. Sound and Vibration* 284, 985-1002 (2005).
5. Butcher, Eric A. and R. Lu, "Constant-Gain Linear Feedback Control of Piecewise Linear Structural Systems via Nonlinear Normal Modes," *J. Vibration and Control* 10, 1535-1558 (2004).
6. Ma, H., E. A. Butcher, and E. Bueler, "Chebyshev Expansion of Linear and Piecewise Linear Dynamic Systems with Time Delay and Periodic Coefficients Under Control Excitations", *J. Dynamic Systems, Measurement, and Control* 125, 236-243 (2003).
7. Butcher, E. A and D. J. Segalman, "Characterizing Damping and Restitution in Compliant Impacts via Modified K-V and Higher-Order Linear Viscoelastic Models," *J. Applied Mechanics* 67, 831-834 (2000).
8. Butcher, E. A., "Clearance Effects on Bilinear Normal Mode Frequencies," *J. Sound & Vib.* 224, 305-328 (1999).

Biographical Sketch - Igor SEVOSTIANOV

Associate Professor, Department of Mechanical Engineering, P.O. Box 30001 Las Cruces, NM 88003-8001
Tel: (505) 646-3322 *Email:* igor@me.nmsu.edu

1.a.i.1. a. Professional Preparation.

1.a.i.2. St. Petersburg (Leningrad) University, Russia (USSR) Mechanics B.S./ M.S., 1988

1.a.i.3. St. Petersburg (Leningrad) University, Russia (USSR) Solid Mechanics PhD, 1993

1.a.i.4.

b. Appointments.

- 2001 – present Assistant and Associate Professor, NMSU, Las Cruces, NM
- 1998-2001 Senior Research Associate, Tufts University, Medford, MA
- 1997-1998 Senior Research Associate, University of Natal, Durban, South Africa
- 1993-1996 Visiting Scientist, Max-Planck Institute, Dresden, Germany

c. Grants.

Current grants

- "Novel Nanoparticle-Filled Matrices for Thermal Stress Reduction in Polymer Matrix Composites: Multi-Scale Modeling and Experimental Validation" from NASA. (2007-2009)

1.a.i.4.1.1.1.Former research grants

- "Acquisition of a Tensile and Compression Test Capability for Characterization of Advanced Materials" from NSF (2005-2007)
- "Macroscopic stress-strain relations with microcracks – generated inelasticity" from Sandia National Labs (2004).
- "Critical Issues and Unresolved Problems in Computational Modeling Supporting Ceramic Armor Analysis" from Sandia National Labs (2003)

d. Awards

NMSU Research Council Award, 2006.
ME Academy Professor of the Year, 2007.

e. Ten key publications. (Total number of referred publications - 84, current ISI citation index 163, self references and references by co-authors are excluded).

Sevostianov, I. and Kachanov, M. Nanoparticle reinforced materials: effect of interphase layers on the overall properties. *International Journal of Solids and Structures* 44 (2007) 1304-1315.

Sevostianov, I., Kováčik, J. and Simančík, F. Elastic and electric properties of closed-cell aluminum foams. Cross-property connection *Materials Science and Engineering, A*-420, 87-99.

Sevostianov, I. and Kachanov, M. Plastic yield surfaces of anisotropic porous materials in terms of electric conductivities. *Mechanics of Materials*, **38**, 2006, 908-923.

Kachanov, M. and Sevostianov, I. On quantitative characterization of microstructures and effective properties. *International Journal of Solids and Structures* **42**, 2005, 309-336

Sevostianov, I., Kachanov, M., Ruud, J., Lorraine, P., Dubois, M. Quantitative characterization of microstructures of plasma-sprayed coatings and their conductive and elastic properties. *Materials Science and Engineering-A*, 386, 2004, 164-174.

Sevostianov, I. and Kachanov, M. Connection between elastic and conductive properties of microstructures with Hertzian contacts. *Proceedings of the Royal Society of London: Mathematical, Physical & Engineering Sciences* A-460, 2004, 1529-1534.

Sevostianov, I. Explicit relations between elastic and conductive properties of a material containing annular cracks. *Philosophical Transactions of the Royal Society of London: Mathematical, Physical and Engineering Sciences*, 361, 2003, 987-999.

Sevostianov, I. and Kachanov, M. Explicit cross-property correlations for anisotropic two-phase composite materials. *Journal of the Mechanics and Physics of Solids*, 50, 2002, 253-282.

Sevostianov, I., Gorbatikh, L. and Kachanov, M. Recovery of information on the microstructure of porous/microcracked materials from the effective elastic/conductive properties. *Materials Science and Engineering A*, 318, 2001, 1-14.

Kachanov, M., Sevostianov, I. and Shafiro, B. Explicit cross-property correlations for porous materials with anisotropic microstructures, *Journal of the Mechanics and Physics of Solids*, 49, 2001, 1-25.

Biographical Sketch - Dr. Andrei Zagrai

Assistant Professor, Department of Mechanical Engineering,
New Mexico Institute of Mining and Technology, Socorro, NM, USA
Phone: 505-835-5636, Fax: 505-835-5209, e-mail: *azagrai@nmt.edu*.

Education

Ph. D. Mechanical Engineering, University of South Carolina, Columbia, SC, April 5th, 2002.
M. E. Department of Acoustics, Taganrog State University of Radio-Engineering, Taganrog, Russia, April 24th, 1997.
B. E. Department of Acoustics, Taganrog State University of Radio-Engineering, Taganrog, Russia, June 24th, 1996.

Appointments

Aug. 2006-present Assistant Professor, Department of Mechanical Engineering, New Mexico Institute of Mining and Technology, Socorro, NM
2002-Jul. 2006 Post-Doctoral Fellow and Research Scientist, Department of Civil, Ocean and Environmental Engineering, Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ
1998-2002 Research and Teaching Assistant, Department of Mechanical Engineering, University of South Carolina, Columbia, SC

Selected Honors, Awards, and Scholarships

- March, 2007 – Air Force Summer Faculty Fellow (SFFP) for the 2007.
- December, 2005 – keynote speaker, *International Conference on Advances in Structural Dynamics and its Applications* (*ICASDA*), 7-9 Dec. 2005, Visakhapatnam, India.
- March, 2002 – 1st Place best student paper award of *SPIE's 7th Symposium on NDE for Health Monitoring and Diagnostics*.
- December 21st, 2001 – 2nd Prize best student paper award in structural acoustics and vibration. Acoustical Society of America, American Institute of Physics
- April 20th, 1998 - The National Scholarship of the President of Russian Federation for Education Abroad
- September 10th, 1996 – The National Scholarship of the President of Russian Federation.

Selected Publications (up to 5 publications closely related to the proposed project)

1. Zagrai, A., Donskoy, D., Chudnovsky, A., Golovin, E., (2006) "Nonlinear Acoustic Structural Health Monitoring," ***Invited Paper***, 106-SDM-67 *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Newport, RI.
2. Giurgiutiu, V., Zagrai, A. (2005) "Damage Detection in Thin Plates and Aerospace Structures with the Electro-Mechanical Impedance Method", International Journal of Structural Health Monitoring, Vol. 4, N. 2, pp. 99-118.
3. Zagrai, A., (2005) "Intelligent Active Sensors for Structural Health Monitoring," ***Keynote Paper***, *Proceedings of the International Conference on Advances in Structural Dynamics and its Applications* (ICASDA), pp. 568-598, 7-9 Dec. 2005, Visakhapatnam, India.
4. Giurgiutiu, V., Zagrai, A.N. (2002) "Embedded Self-Sensing Piezoelectric Active Sensors for On-line Structural Identification," Transactions of ASME, *Journal of Vibration and Acoustics*, Vol. 124. N. 1, pp. 116-125.
5. Zagrai, A.N., Giurgiutiu, V. (2001) "Electro-Mechanical Impedance Method for Crack Detection in Thin Plates", *Journal of Intelligent Material Systems and Structures*, Vol. 12, N. 10, - October 2001, pp. 709-718.