NEW MEXICO EPSCOR
STRUCTURAL HEALTH MONITORING AND SELF-HEALING OF AEROSPACE STRUCTURES

Progress Report
Grant number: NNX07AT64A
Structural Health Monitoring of Aerospace Structures

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Progress Report Compiled by:
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Structural Health Monitoring and Self-Healing of Aerospace Structures
New Mexico NASA EPSCoR - NNX07AT64A
Progress Report 10.31.10

Research accomplishments measured against the proposed goals and objectives:

Objective #1: 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 embedded nonlinear ultrasonic wave interrogation.
Two new approaches were proposed for structural health monitoring of aerospace structures. 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 (Butcher, Sevostianov, Zagrai). The second approach is attributing to damage in joints and connections an importance commensurate with fracture and fatigue damage that develops in the structural material (Burton, Butcher, Sevostianov). The research outcomes will be useful for many aerospace structures, including aircraft structures and engines, launch vehicles, space vehicles, permanent structures placed on the moon or Mars, and robotic devices that patrol these structures for SHM.

Progress on Objective #1:
A wide range of studies are available on vibration-based detection and identification of fatigue cracks in simple and complex structures. Our progress on this objective involves the application of the electromechanical impedance method and nonlinear resonance measurements to high frequency detection of incipient fatigue damage in aluminum alloy specimens. In this study, the electromechanical impedance method is utilized for assessment of material deterioration under cyclic fatigue loads. Piezoelectric wafer active sensors were utilized for transmission and reception of elastic waves. Variations in structural dynamic characteristics were considered for different excitation conditions and increasing damage severity. Two-dimensional aluminum specimens were subjected to increasing fatigue cycles at stress amplitudes below the yield point, and electromechanical impedance signatures were taken at discrete levels of fatigue damage. Linear and nonlinear features of the impedance signatures were compared for different damage conditions. Spectral measurements demonstrated that the downward frequency shift dependency observed in 1-D dog bone specimens with increasing fatigue levels is also apparent in 2-D structures undergoing fatigue. As in the previous experiments with 1-D samples, it was observed in the 2-D specimens that the frequency shifts occurred before the appearance of a visible crack, which indicates the method's sensitivity to incipient fatigue damage before crack initiation and growth. The changes in average amplitude level for the impedance analyzer low-frequency and high-

Figure : Plate sample (2-D) mounted in loading jig of MTS load frame for real-time acoustic measurements.

frequency tests also correlate with the increased level of fatigue. Nonlinear harmonic measurements were conducted on fatigued aluminum samples. A general increasing trend was observed for the second harmonic amplitude data, which would indicate increasing levels of material nonlinearity, but consistency of the data needs to be verified in future tests.

The methodology and results developed in years 1-2 of the project to distinguish between damage accumulated in structural members and in joints, which is based on the combined approach of electrical conductivity and natural vibration frequency measurements, has been extended in year 3. Specifically, explicit formulas have been obtained for the case of longitudinal vibrations of bars clamped with a damaged bolted joint and interior damage due to macrocracks, and two approximation methods (Chebyshev spectral collocation and asymptotic analysis) have been used for Kirchoff and Mindlin plates, non-uniform and rotating beams, and beams and plates with nonconservative loads. Furthermore, a method of exciting a damaged structure with a hyperchaotic probe has been developed which allows for the estimation of damage by comparing geometric attractor metrics for the undamaged and damaged structures. Experimental verification of this technique has been done at the Univ. Cal. San Diego. In addition, finite element analysis has been combined with the Local Equivalent Linear Stiffness Method (LELSM) to determine the effects of multiple breathing cracks on vibration frequencies.

A novel method of reduced order modeling using an iterated Local Equivalent Linear Stiffness Method and Ritz vectors, which is comparable in accuracy to the popular Principal Orthogonal Decomposition (POD) technique but avoids the need for *a priori* simulation of the mathematical model, has been tested and has demonstrated promise for SHM applications with combined joint/material damage. Also, a combined finite element/ harmonic balance analysis has been used to detect the locations and depths of cracks in rotating shafts by analyzing the changes in the forward and backward whirl frequencies. The team has recently developed new models of breathing functions for cracked rotating shafts which represent the time-varying change in local stiffness and area moment of inertia much better than in the previous literature. This theoretical and computational work has been validated experimentally using a SpectraQuest rotordynamic system. Finally, the effects of rough surfaces on the micro-slip of bolted joints have been studied by linking microscopic surface roughness parameters to macroscopic parameters in parallel–series Iwan models. This has lead to analytical expressions for the energy dissipated in bolted joints, for instance, in terms of these tribological parameters.

A new methodology for detecting a self-loosening failure in bolted joints that uses electrical resistance as a diagnostic parameter has been developed. It is based on the phenomenon that the electrical constriction resistance of the rough contact interface between two conductive members clamped by the bolt is a sensitive indicator of bolted joint integrity. A simple formula for relationship between relative electrical conductance changes and relative tightening torque changes is analytically obtained.

A new concept for monitoring of strength reduction due to accumulated damage has been proposed and verified (experimentally and numerically). The key parameter for monitoring is not the reduction of the average (over the specimen) stiffness but its *local* minimal values caused by formation of defect clusters. These defect clusters can be identified by the emergence of spatial *gradients* of elastic stiffness on a smaller scale. A convenient tool of detecting these gradients is

provided by the elasticity-conductivity connection: the electric conductance gradient is usually easier to measure than the stiffness gradient.

In the vibration based experimental work, we completed the fabrication of test specimens, mounting hardware, and the measurement system, which consists of very light accelerometers mounted at several locations on the specimens. The data gathering system is operational for impulse testing. The capability to test a cantilever-free beam with non-ideal cantilever boundary conditions is operational; here the tightening torque on the bolted, cantilevered end can be controlled to simulate ideal and varying levels of non-ideal connection. We have just recently taken a set of decay test data for a matrix of test conditions (bolted joint tightening torque is the parameter). These data will be analyzed in the coming month to determine the effect of non-ideal connection on the modal damping parameters to test the hypothesis that damping can be used as a discriminant to characterize connection joint/connection damage. Additional experiments of this type will be conducted through the remainder of the contract period.

Objective #2: Develop self-repairing materials for aerospace structures subjected to accumulated damage and use the proposed SHM methods to monitor the self-healing process.

Progress on Objective #2: Based on our newly developed composite material, following three primary regions of oxidation process can be identified: (I) Fe_2O_3/Fe_3O_4 external scales + Cr_2O_3/Al_2O_3 internal scales, (II) $Cr_2O_3/Fe(Cr, Al)_2O_4$ external scale + Al_2O_3 internal scales and (III) external scale of only Al_2O_3. The role of the high chromium content in producing TGO Al_2O_3 scales at such lower aluminum content and then in binary Fe-Al alloys can be described by considering the transient oxidation phenomena for a Fe-45%Cr-4%Al-0.3%La at 1200^OC shown schematically in Figure 2. The initial oxide scale (Figure 2a) contains all the cations of the alloys surface which is composed of the mixture of the nanocrystallite oxides $Cr_2O_3/Al_2O_3/Fe_2O_3$ (Figure 2b). The subscale formation of Al_2O_3 occurs because it is stable at the low oxygen activity defined by the mixture of $Cr_2O_3/Fe(Cr,Al)_2O_3$ alloy equilibrium and internal oxidation of Al occurs ahead of this front since Al_2O_3 is stable at even lower oxygen activities here. The high chromium content results in a Cr_2O_3 subscale, which may be continuous (Figure 2c) and defines a lower scale-alloy oxygen activity. It reduces the oxygen diffusion, and curtails internal Al_2O_3 formation. Further growth of $Cr_2O_3/Fe(Ce,Al)_2O_4$ will be blocked. Eventually, the Al_2O_3 subscale becomes continuous and its rate will be controlled. Thus, on the surface of the alloy specimen with a Beilby layer at 1200^OC, conditions for scale formation even at the initial stages of the oxidation (when the oxide scale thickness does not exceed a few microns) the barrier scale for cation and anion counter diffusion structure (architecture) will be developed. This finally will lead to the formation of slow growing and adherent (due to the alloying with RE elements) TBC which protects metal matrix against a high temperature corrosion. Figure 2a corresponds to the transformation of Beilby layer into the oxide layer which is a mixture of nanocrystallites of all element oxides composing the alloy, during the first oxidation minutes at 1200^OC. The following schemes (Figures 2b and 2c) illustrate a possibility of the continuous formation of the TGO out of Al_2O_3 on the investigated alloy in spite of the low Al content (<5%) in it. These figures also demonstrate a mechanism of the self-organized TBC with the self healing potential on the alloy surface at high temperatures. The reservoir under TBC supplies Al (as well as Cr) atoms required for the reproduction of the healing agents on the crack surfaces (in case of their appearance in the coating) in the form of Al_2O_3 particles (as well as of Cr_2O_3, partially). The formation of TBC on

the Fe-45%Cr-5%Al-0.3%La alloy will allow creating a metal/metal/ceramics composition with a functionally distributed sandwich architecture characterized with the self healing features similar to that of the wound on the skin. Here it is given the schematic of the structure (architecture) on the substrate which is placed together with the cross section of the skin.

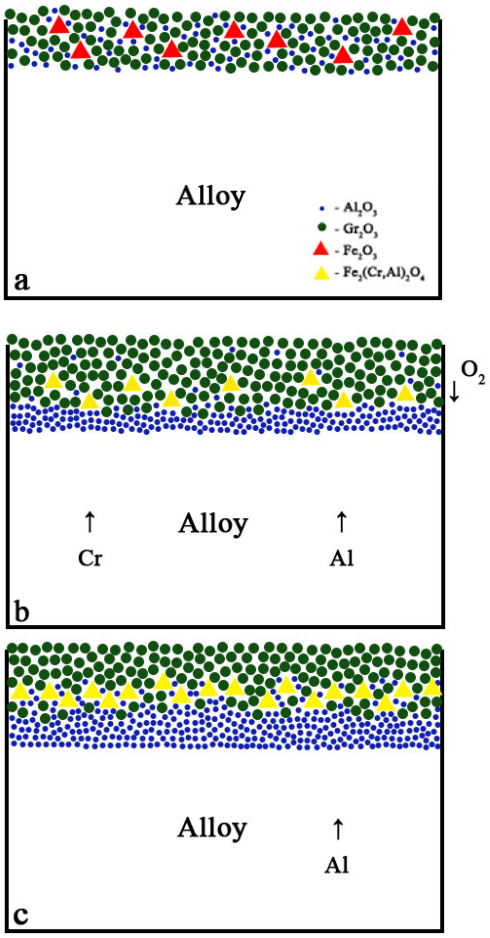

Figure 2. Synergistic effects of high chromium content on the formation of Al_2O_3 TGO scales during the transient oxidation of Fe-45%Cr-5%Al-0.3%La alloy at 1200^0C after (a) 10 min, (b) 1hr and (c) 10hrs.

Objective #3: Contribute to strengthen New Mexico aerospace engineering educational and research programs at New Mexico State University (NMSU) and New Mexico Institute of Mining and Technology (NMT) and use the aerospace programs to interest New Mexico K-12 students in the Science Technology Engineering Math (STEM) disciplines.

Progress on Objective #3: In December, 2009 NMSU proposals for MS and PhD degrees in Aerospace Engineering were approved by the New Mexico State Board of Finance, the final step in the approval process. . These graduate degrees will be effective Fall, 2011. In making the case for these graduate programs the NASA EPSCoR project was cited as an example of aerospace research currently ongoing at NMSU and as an example of the type of research that will be done in the future by students in the MSAE and PhD AE programs. These graduate AE programs at

NMSU will involve a three-way distance education collaboration among NMSU, NMT, and the University of New Mexico in the delivery of aerospace and related courses. The NMSU AE graduate programs will be essential in enabling us to attain national competitiveness for research and scholarly activity.

The NMSU AE undergraduate program has been strengthened by a grant from New Mexico SpaceGrant to one of the EPSCoR coPI's (Eric Butcher). The purpose of this grant was to allow Dr. Butcher to develop a modern undergraduate course in Orbital Mechanics (NMSU course AE 362) through incorporation of a number of novel case studies, examples, and trajectory design methodologies. Eventually, this work will be incorporated into a graduate course in orbital mechanics that is being planned by Dr. Butcher. This grant was a direct result of the collaboration with SpaceGrant that developed as a result of the NASA EPSCoR project.

Objective #4: Develop nationally competitive research expertise and research programs in the proposed and related areas in preparation for obtaining follow-up research funding.

Progress on Objective #4: As noted later in this report, the research group has been active in publishing research results in quality journals and at technical conferences. A number of proposals in the same or relevant technical areas have been submitted, and several of these have been funded. Thus, through Year 3 we have demonstrated significant research accomplishment and good success in securing follow-on funding to support research in SHM and related areas.

Objective #5: Develop collaborations with key entities in New Mexico, Los Alamos National Laboratory (LANL), Sandia National Laboratories and with relevant NASA Centers, enhancing the prospects for future nationally competitive research.

Progress on Objective #5: The collaboration with Los Alamos National Lab that led to a funded project in health monitoring during Years 1 and 2 has progressed well. The LANL collaborators bring their extensive experience in sensing and hardware applicable to health monitoring to complement the theoretical work being done by the NMSU group. This marriage of real-world and theoretical research has been of direct benefit to the NASA EPSCoR research project. One of the NMSU graduate students (Krystal Deines) funded by this EPSCoR project participated in the NSF sponsored Summer Dynamics School run by LANL during the summer of 2010; Ms. Deines worked on a student research team conducting health monitoring studies of wind turbine blades.

Research success of individual investigators as measured by:

Special Journal Issues Published

Burton, T., Hynes, P. and Sevostianov, editors, Special Issue: Structural Health Monitoring in the Light of Inverse Problems in Mechanics, *Intl. J. Engineering Science*, **48**(10) (2010)

Journal articles published or in press (does not include articles reported in year 1 and 2 progress reports)

- Sevostianov, I., Zagrai, A., Kruse, W.A., Hardee, H.C. (2010) "Connection Between Strength Reduction, Electric Resistance and Electro-Mechanical Impedance in Materials with Fatigue Damage," International Journal of Fracture, OnlineFirst, DOI: 10.1007/s10704-010-9487-4.
- Zagrai, A., (2009) "Emerging Technologies for Structural Damage Detection and Evaluation," i-manager's Journal on Future Engineering and Technology, Vol. 4, N. 2, November 2008 – January 2009, pp. 1-16.
- Argatov, I.I. and E.A. Butcher, "On the Iwan Models for Lap-Type Bolted Joints," *International Journal of Nonlinear Mechanics,* doi:10.1016/j.ijnonlinmec.2010.09.018 (2010).
- Al-Shudeifat, M.A. and E.A. Butcher, "New Breathing Functions for the Transverse Breathing Crack of the Cracked Rotor System: Approach for Critical and Subcritical Harmonic Analysis," *Journal of Sound and Vibration*, 330, 526-544 (2010).
- Al-Shudeifat, M.A. and E.A. Butcher, "Order Reduction of Forced Nonlinear Systems using Updated LELSM Modes with New Ritz Vectors," *Nonlinear Dynamics*, 62, 821-840 (2010).
- Al-Shudeifat, M.A., E.A. Butcher, and C. Stern, "General Harmonic Balance Solution of a Cracked Rotor-Bearing-Disk System for Harmonic and Sub-harmonic Analysis: Analytical and Experimental Approach," *International Journal of Engineering Science* 48, 921-935 (2010).
- Sari, M. and E.A. Butcher, "Natural Frequencies and Critical Loads of Beams and Columns with Damaged Boundaries using Chebyshev Polynomials," *International Journal of Engineering Science* 48, 862-873 (2010).
- **Sevostianov, I.** Incremental elastic compliance and electric resistance of a cylinder with partial loss in the cross-sectional area. *International Journal of Engineering Science* **48** (2010), 582-591. (mentioned last year as submitted)
- **Sevostianov I.** and Kachanov M. Local minima and gradients of stiffness and conductivity as indicators of strength reduction of brittle-elastic materials. *International Journal of Fracture* **164** (2010), 147-154.
- Argatov, I and **Sevostianov, I.** Health monitoring of bolted joints via electrical conductivity measurements. *International Journal of Engineering Science* **48** (2010), 874-887.
- **Sevostianov, I.**, Zagrai, A., Kruse, W.A., and Hardee, H. Connection between strength reduction, electric resistance and electro-mechanical impedance in materials with fatigue damage. *International Journal of Fracture* **164** (2010), 159-166.
- **Sevostianov, I.** and Kushch, V.I., Effect of pore clusters on the statistics of peak stress and overall properties of porous material. *International Journal of Solids and Structures* **46** (2009) 4419-4429.
- Cramer, M. and **Sevostianov, I.** Effect of pore distribution on elastic stiffness and fracture toughness of porous materials. *International Journal of Fracture* **160** (2009), 189-196.

Journal articles in press

- Ervin, J. and **Sevostianov, I.** Effect of geometric characteristics of a cluster of microcontacts on its mechanical and electrical properties. *International Journal of Theoretical and Applied Multiscale Mechanics* (in press)

- Argatov, I and **Sevostianov, I.** Rigid toroidal inhomogeneity in an elastic medium. *International Journal of Engineering Science* (in press).
- Picazo, M. and **Sevostianov, I.** On the elastic compliance of a circular hole with two symmetric radial cracks initiated at its boundary *International Journal of Fracture* (in press).
- **Sevostianov, I.** and Kachanov, M. Elastic fields generated by inhomogeneities: Far-field asymptotics, its shape dependence and relation to the effective elastic properties. (submitted).
- Dominguez, D. and **Sevostianov, I.** Cross-property connection between work-hardening coefficient and electrical resistivity of stainless steel during plastic deformation *International Journal of Fracture* (in press).

Journal articles submitted during the third year of the project

- Sari, M. and Butcher, E. A., "Free Vibration Analysis of Static and Rotating Timoshenko Beams with Damaged Boundaries by the Chebyshev Collocation Method," *Computers and Structures*, submitted.
- Sari, M., Nazari, M., and Butcher, E. A., "Effects of Damaged Boundaries on the Free Vibration of Kirchoff Plates," *J. Sound and Vibration*, submitted.
- Torkamani, S., Butcher, E.A., Todd, M.D., Park, G.P., "Detection of System Changes due to Damage using a Tuned Hyperchaotic Probe," *Smart Materials and Structures*, revision submitted.
- Argatov, I.I. and E.A. Butcher, "On the Separation of Internal and Boundary Damage in Slender Bars using Longitudinal Vibration Frequencies and Equivalent Linearization of Damaged Bolted Joint Response," *Journal of Sound and Vibration*, submitted.
- Butcher, E. A., Al-Shudeifat, M. A., "An Efficient Mode-Based Alternative to Principal Orthogonal Modes in the Order Reduction of Structural Dynamic Systems with Grounded Nonlinearities," *Mechanical Systems and Signal Processing*, revision submitted.
- Aizikovich, S., Krenev, L., **Sevostianov, I.**, Trubchik, I., and Evich, L. Evaluation of the elastic properties of a functionally-graded coating from the indentation measurements (submitted).

Conference Papers submitted and accepted

- E. R. Kutelia, S. I. Bakhtiyarov, M. N. Okrosashvili, O. O. Tsurtsumia, B. P. Bulia, A. S. Bakhtiyarov and B. G. Eristavi, 2010, "Development of High-Temperature Corrosion and Creep Resistant Nb, Mo and Cr based Compositions with Protective Self-Healing Coating of Fe-45%Cr-4%Al-1%Ni-0.3%La Alloy", **Journal of Materials Science and Engineering** (submitted).
- E. R. Kutelia, S. I. Bakhtiyarov, O. O. Tsurtsumia, A. I. Bakhtiyarov and B. Eristavi, 2010, "Development of High Temperature Self-Healing Coating Systems", **International i-Manager's Journal on Future Engineering & Technology,** Vol. 5, No. 3, pp. 10-14.
- L. N. Rukhadze, E. R. Kutelia, N. I. Maisuradze, B. G. Eristavi and S. I. Bakhtiyarov, 2009, "Preparation and Characterization of Carbon Nanoparticles Doped with Magnetic Clusters", **Georgian Engineering News**, No. 4, pp. 56-59.
- E. Kutelia, O. Tsurtsumia, S. I. Bakhtiyarov, H. Adanir, B. Bulia, O. Mikadze and B. Eristavi, 2009, "Obtaining the Self-Organizing Thin Protective Thermal-Barrier and

Tribological Coatings on the Surface of Fe-44%Cr-4%Al-0.3%La Alloy", **Journal of Plasma Processes & Polymers (Wiley-VCH)** (submitted).

- Butcher, E.A., Sari, M., and Nazari, M., "Free Vibration Analysis of Kirchoff Plates with Damaged Boundaries by the Chebyshev Collocation and Perturbation Methods," ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems, Sep. 28-Oct 1, 2010, Philadelphia, PA.
- Torkamani, S., Butcher, E.A., Todd, M.D., Park, G.P., "Damage Assessment Using Hyperchaotic Excitation and State Space Geometry Changes," ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems, Sep. 28-Oct 1, 2010, Philadelphia, PA.
- Al-Shudeifat, M. and E. A. Butcher, "On the Modeling of Open and Breathing Cracks of a Cracked Rotor System," proceedings of 2010 ASME IDETC, Montreal, Quebec, Aug. 15-18, 2010.
- Sari, M. and E.A. Butcher, "Free Vibration Analysis of Kirchoff Plates with Damaged Boundaries by the Chebyshev Collocation Method," Symposium on Mechanics of Slender Structures (MOSS 2010), Donostia – San Sebastian, Spain, July 21-23, 2010.
- Al-Shudeifat, M. A., E. A. Butcher, and T. D. Burton, "Enhanced Order Reduction of Forced Nonlinear Systems using New Ritz Vectors," Proc. 28th International Modal Analysis Conference, Jacksonville, FL, Feb. 1-4, 2010.
- Torkamani, S., Butcher, E.A., Todd, M.D., Park, G.P., "Damage Assessment Using Hyperchaotic Excitation and State Space Geometry Changes," 2010 Inverse Problems Symposium, June 6-8, 2010, East Lansing, MI.
- Al-Shudeifat, M. and E. A. Butcher, "On the Dynamics of a Beam with Switching Crack and Damaged Boundaries: Application of the Local Equivalent Linear Stiffness Method," 13th Conference on Nonlinear Vibrations, Dynamics, and Multibody Systems, VPI&SU, Blacksburg, VA, May 23-27, 2010.
- **Sevostianov, I.** Explicit cross-property connections for materials with anisotropic constituents. (XI Panamerican Congress on Applied Mechanics, Foz do Iguacu, Brazil, 2010);
- **Sevostianov, I.** Effect of clusters of microdefects on elastic, conductive and fracture properties of materials. (EMI-2010, Los Angeles, August 2010);
- Picazo, M., and **Sevostianov, I.** Effect of branched cracks on the elastic compliances. (22-nd Rio Grande Symposium on Advanced Materials, Albuquerque, NM, 2010);
- Dominguez, D. and **Sevostianov, I.** Cross-property connection between strength-hardening coefficient and electrical resisitivity of stainless steel during plastic deformation. (22-nd Rio Grande Symposium on Advanced Materials, Albuquerque, NM, 2010).
- **Sevostianov, I.** Effect of clusters of microdefects on elastic, conductive and fracture properties of materials. (22-nd Rio Grande Symposium on Advanced Materials, Albuquerque, NM, 2010).
- Burton, T.D., K.E. Deines and J.A. Mercer, "Nonlinear Normal Modes in a Weakly Nonlinear System with Internal Resonances," 13th Conf. on Nonlinear Vibrations, Dynamics, and Multibody Systems, Blacksburg, VA, May (2010).
- Kumar, N and T.D. Burton, "On Reduced Order Modeling in Nonlinear Structural Dynamics," IUTAM Symposium on Nonlinear Dynamics for Advanced Technologies and Engineering Design, Aberdeen, Scotland, July 27-30 (2010).

Conference papers submitted during the 3rd year of the project

1. E. R. Kutelia, O. Tsurtsumia and S. I. Bakhtiyarov, 2010, "Relatively Simple and Low Cost Technique of New Metal-Ceramic Medical Implants on the Basis of Fe-Cr-Al-RE Alloy", Abstract, **NACE Corrosion 2010 International Conference and Expo,** San Antonio, TX, March 14-18, 2010.
2. E. R. Kutelia, S. I. Bakhtiyarov, O. Tsurtsumia, A. S. Bakhtiyarov, and B. Eristavi, 2009, "High-Temperature Self-Healing Metallic Coating: Concepts and First Results", Proceedings, **ASME Fluids Engineering Division Summer Meeting,** Symposium on Transport Phenomena in Manufacturing Processes, Vail, CO, August 2-5, 2009.
3. Zagrai, A., (2010) "Embedded Ultrasonic Characterization of Interfaces in Space Structures," AFOSR Workshop on Improved Precision for Space Systems, 27-28 May 2010, Albuquerque, NM.
4. Zagrai, A., Gigineishvili, V., Kruse, W., Murray, A., Doyle, D., Reynolds, W., Arritt, B., Gardenier, H., (2010) "Acousto-Elastic Measurements and Baseline-Free Assessment of Bolted Joints using Guided Waves in Space Structures," SPIE's 17th Annual International Symposium on Smart Structures and Materials and 15h Annual International Symposium on NDE for Health Monitoring and Diagnostics, 7-11 March 2010, San Diego, CA, v 7650, n PART 1, paper 7650-41, pp. 765017-1-12.
5. Kruse, W., Gigineishvili, V., Zagrai, A., (2010) "Fatigue Damage Assessment using High Frequency Resonance Measurements," SPIE's 17th Annual International Symposium on Smart Structures and Materials and 15h Annual International Symposium on NDE for Health Monitoring and Diagnostics, 7-11 March 2010, San Diego, CA, v 7650, n PART 1, paper 7650-53, pp. 76501J-1-12.
6. Kruse, W., and Zagrai, A.N. (2009) "Investigation of Linear and Nonlinear Electromechanical Impedance Techniques for Detection of Fatigue Damage in Aerospace Materials," Proceedings of 7th International Workshop of Structural Health Monitoring, 9-11 September 2009, Stanford University, California, pp.1840-1847.

Patents: none

Follow-on grant proposals submitted/funded including funding amounts during the 3rdd year of the project

- PI: **"Design and Development of Modified Spiral Orbital Tribometer (MSOT) and Tribological Properties Measurements on High Temperature Ionic Lubricants",** DoD AFRL, Air Force Defense Research Sciences Program, Small University Grants ($50,000 for 1 year)
- PI: **"PFI: Partnership for Innovative Turbo-Gen Technology to Generate Energy from Multiple Geo-Pressurized Sources",** NSF PFI **(Letter of Intent, October 2010).**
- PI: Andrei Zagrai, "Structural Integrity Assessment using Piezoelectric and Magneto-Elastic Active Sensors," DOD ARL, $309,973 (submitted)
- PI: Andrei Zagrai, "Focused Learning Strategy for Improving Competitiveness of STEM Students with Disabilities," NSF RDE, $164,082. (submitted and not awarded).
- PI: Andrei Zagrai, "A Scanning Laser Doppler Vibrometer for Space Systems Research and Aerospace Education," DOD DURIP, $330,850 (submitted and not awarded).
- Multiscale materials characterization for modeling of multiphysics processes in heterogeneous materials with hierarchical structure (DOE)

- Cross-property connections for microcracked materials: assessment of strength reduction from the measurements of electrical resistance (NSF)
- Assessment of strength reduction due to accumulated damage in fatigued materials using cross-property connections (NASA-space grant consortium)
- Advancement of micromechanical criteria for fracture toughness (NASA-space grant consortium).

Improvements in jurisdiction research and development infrastructure

- NMSU: Development of an experimental facility for vibration based health monitoring has been completed in year 3 and is now operational.. We have also initiated development of a fatigue testing facility that will enable experimental study of distributed micro-damage. The new experimental facilitieswill significantly improve NMSU's capabilities in SHM and DP in year 4 and beyond.

Systemic change as evidenced by:

- Reordered jurisdiction and/or institutional priorities: This research program has not yet had a significant influence on institutional priorities.
- Increased financial commitment from the jurisdiction, industry, and participating institutions: This research program is successful in receiving 100% matching funds from the participating institutions and State of New Mexico. This was a significant financial commitment by NMSU.

Examples of successful transfer of technology to the private sector:

- Dr. Butcher and PhD student M. Shudeifat have collaborated during year 3 with Management Sciences, Inc. in Albuquerque to develop a new SHM approach for damaged rotating shafts.

Extent to which collaborations with jurisdiction agencies, industry, research and academic institutions and with NASA have evolved:

- (*see above*)Dr. Butcher and PhD student M. Shudeifat have collaborated during year 3 with Management Sciences, Inc. in Albuquerque to develop a new SHM approach for damaged rotating shafts.
- (*see also above*) The opportunity that Krystal Deies had to spend the summer in the Los Alamos Summer Dynamics School was enabled by her experience working in the NASA EPSCoR program and enhanced the already close collaboration in SHM research with LANL.
- NMSU recently was awarded the FAA COE for Commercial Space Transportation (Dr. Hynes is the PI) as leader in a coalition of a number of universities. Research collaboration with the University of Central Florida has been initiated recently in structural health monitoring as part of this project.
- To better fit within the branch research mission, for this project Dr. Baaklini recommended close collaboration with Dr. John Lekki – an expert in integrated vehicle monitoring. Interaction with Dr. Lekki has led to the concept of the future collaboration in which the proposed SHM methodologies will complement existing NASA Glenn efforts in SHM of aerospace systems.
- Dr. John Lekki, Optical Systems Research Engine, NASA Glenn Research Center

- More involvement with NASA personnel is a priority for Year 4.

Evidence of how EPSCoR activities have furthered jurisdiction priorities: Structural health monitoring and damage prognosis are now recognized as important research areas in the NMSU College of Engineering..

Discussion of interaction between and cooperation with the jurisdiction Space Grant program:

(*The following paragraph also appears above* The NMSU AE undergraduate program has been strengthened by a grant from New Mexico SpaceGrant to one of the EPSCoR coPI's (Eric Butcher). The purpose of this grant was to allow Dr. Butcher to develop a modern undergraduate course in Orbital Mechanics (NMSU course AE 362) through incorporation of a number of novel case studies, examples, and trajectory design methodologies. Eventually, this work will be incorporated into a graduate course in orbital mechanics that is being planned by Dr. Butcher. This grant was a direct result of the collaboration with SpaceGrant that developed as a result of the NASA EPSCoR project.

In addition, researchers at both New Mexico State University and New Mexico Institute of Mining and Technology work closely with New Mexico Space Grant Consortium. Researchers attended the Space Grant annual meeting, gave program updates, and discussed research opportunities with other Space Grant supported researchers.

Dissertations and Theses:

- Al-Shudeifat, M., *New Techniques for Order Reduction and Damage Detection in Structural and Rotordynamic Systems*, PhD Thesis, New Mexico State University (2010).
- Dominguez, D., MS Thesis, New Mexico State University (2010).
- Picazo, M., MS Thesis, New Mexico State University (2010).

Demographic (ethnicity/race and gender through self identification) information on participants:

- Faculty – including names and institutions
  - Sayavur Bakhtiyarov (New Mexico Institute of Mining and Technology) – white/male
  - Andrei Zagrai (New Mexico Institute of Mining and Technology) – white/male
  - Thomas Burton (New Mexico State University) – white/male
  - Igor Sevostianov (New Mexico State University) – white/male
  - Eric Butcher (New Mexico State University) – white/male
- Post-doctoral researchers, graduate, and undergraduate students
  - Ma'en Sari (PhD student funded by NMSU cost sharing) – white/male
  - Mohammed Al-Shudeifat (PhD student funded by NMSU cost sharing) - white/male
  - Shahab Torkamani (PhD student funded through NMSU Graduate Research Enhancement Grant and LANL MOU grant) – white/male
  - Morad Nazari (PhD student funded by NMSU cost sharing) – white/male
  - Joshua Mendoza (BS undergraduate student funded by NASA EPSCoR grant) – Hispanic/male

- Christopher White (BS undergraduate student funded by NASA EPSCoR grant) – white/male, student registered with the disability services.
- Julie Mercer (MS graduate student funded by NASA EPSCoR grant) – white/female
- Krystal Deines (MS graduate student funded by NASA EPSCoR grant) – white/female
- Mario Picazo (MS graduate student funded by NASA ESPSCoR grant)-Hispanic/male
- David Dominguez (MS graduate student funded by Nasa EPSCoR grant-Hispanic/male
- Akshin Bakhtiyarov (MS graduate student funded by NASA EPSCoR grant) – white/male
- Erica Summers (BS undergraduate student funded by NASA EPSCoR grant) – Hispanic/female
- Dunte Hector (BS undergraduate student funded by NASA EPSCoR grant) – Black/male
- Anais Linan (BS undergraduate student funded by NASA EPSCoR grant) – Hispanic/female
- Marcus Cramer (MS graduate student funded by NASA EPSCoR grant) – white/male
- Walter Kruse (MS graduate student funded by NASA EPSCoR grant) - white/male
- Vlasi Gigineishvili (MS graduate student supported by local funds and has volunteered for some work on the project; however was not supported by NASA EPSCoR; he is not a US citizen) – white/male

Schedule of Program Activities for Years 3/4	
Milestone	**Year 3/4**
Basic research in four areas	**********
Design validation experiments	Done in 3
Conduct validation experiments	**********
Integrated multi-scale methodology development	**********
Methodology validation	**********
Deliverable: validated methodology	**********
NASA panel evaluations	**********
Statewide/NASA joint research	**********