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

Progress Report
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Structural Health Monitoring of Aerospace Structures

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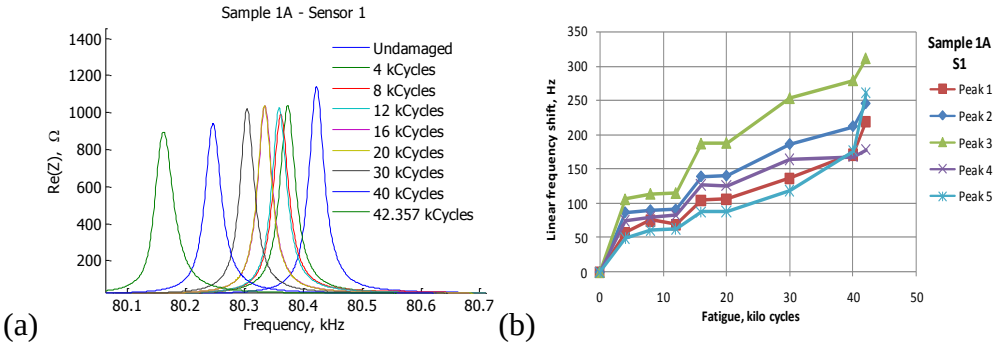
Structural Health Monitoring and Self-Healing of Aerospace Structures
New Mexico NASA EPSCoR
Progress Report – Year 2

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, Zagrei). 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: Developments in high frequency embedded ultrasonics are aimed at facilitating detection of incipient material damage. Nonlinear and linear methodologies are considered that enable monitoring micro-scale material degradation before crack development and material fracture. The nonlinear techniques were developed for embedded ultrasonic detection of micro-scale fatigue damage and included nonlinear electro-mechanical impedance and nonlinear ultrasonic resonance. It has been determined that although both techniques are capable of detecting the fatigue damage, resonance technique showed more promising damage detection capabilities.

During development of nonlinear techniques it was found that electro-mechanical impedance in its linear implementation at ultrasonic frequencies reveals high sensitivity to fatigue damage. This method was able not only to detect, but also assess severity of fatigue damage. Our experimental data show clear correlation between frequency deviation of impedance peaks and a number of fatigue cycles sustained by the test specimen (Fig. 1). The correlation of the electro-mechanical impedance data and the micro-scale fatigue damage before crack development and material fracture has been shown for the first time and may be instrumental in prognosis and life prediction of aerospace structural elements.
Modeling efforts were directed towards better understanding of the electromechanical impedance methods and its practical use for embedded ultrasonic SHM. A conference paper on this topic has been submitted and journal paper is in preparation.



(a) (b)

Figure 1 (a) Real part of impedance collected at increasing number of fatigue cycles; (b) shift of impedance peaks at increasing number of fatigue cycles.

Experiments incorporating structural specimens having simulated damage at connections/joints, distributed micro-damage, and/or isolated macro-damage have been designed. Fee and forced vibration tests with one, two or all three damage types will be conducted during year 3. In addition recent experimental fatigue results have shown significant reductions in local strength, and vibration based damage detection will be used to determine whether such localized fatigue can be detected by vibration-based SHM.

A methodology has been developed to connect volume average properties (elastic stiffness, electric conductivity etc) with the extreme valued properties (like strength). Preliminary experimental data has been obtained that allows one to estimate accumulated fatigue damage from conductivity scanning - measurement of electrical conductivity variation.
A mathematical methodology has been developed to estimate structural health of the bolted joints from the electrical conductivity measurements. Explicit formulas have been derived that connect the torque applied to the bolts with the conductivity across the bolted plates.

The methodology and results developed in year 1 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 2. Specifically, explicit formulas have been obtained for the case of transverse vibrations of a clamped uniform beam with a damaged boundary, and two approximation methods (based on Chebyshev polynomials and perturbation analysis) have been used for non-uniform beams and columns with damaged boundaries. Furthermore, an optimization method allows the determination of boundary damage parameters given the natural frequencies. In addition, efforts to extend the procedure to the case of three-dimensional vibrations of thick rectangular plates with damaged boundaries using a Chebyshev spectral collocation technique are in progress.

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 shown that the presence of subharmonic frequencies and complex Lissajous figures in the whirl orbits correlates well with the critical depths and locations of both open and breathing cracks. This theoretical

and computational work is being validated experimentally using a SpectraQuest rotordynamic system.

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: The compositions were obtained on the Nb and Mo monocrystals and low alloyed Cr bulk samples coated with Fe-45%Cr-4%Al-1%Ni-0.3%RE (La, Y) alloy using EB-PVD technique. SEM, WDS, AES and LM investigations were carried out. The following results were obtained:

- The refractory metals base metal/metal composition with an overlay coating of heat resistant alloy of ultra-fine grain structure after the pre-oxidation at $1200^{O}C$ transforms into the combined metal/metal/ceramic compositional material of the sandwich structure as association the multi-layer architecture of hybrid materials with the distributed different functional behaviors.
- The metallic-oxide hybrid layer formed on the surface of synthesized compositions at high working temperatures has an ability to heal the cracks developed as a result of the mechanical and thermal damages.
- Ultra-fine crystalline structure of both, the overlay coating and the self-organizing TGO protective scale on its surface, provide the relaxation of those stresses caused due to the thermal-expansion mismatch during the co-deformation of metallic matrix with nano-scale crystalline layers (minimizing the probability for crack initiation) and promoting a smooth transition between three regions having different physical-mechanical behaviors.
- The realization of considered structural architecture of the different materials combination, generally, for the obtained compositional material is expressed in the possible collective effects such as: increasing in the damage tolerance, the ability of cracks for the thermally activated self-healing, and the optimal combination of high values of heat resistance and heat proofness.

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 October, 2008 NMSU proposals for MS and PhD degrees in Aerospace Engineering were approved by the NMSU Board of Regents and went to the state of New Mexico Higher Education Department for state approval. The goal is to have these graduate degrees effective Fall, 2010. 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 is being strengthened by a grant from New Mexico SpaceGrant to one of the EPSCoR coPI's (Eric Butcher). The purpose of this grant is 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 2 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 Year 1 is progressing 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 is of direct benefit to the NASA EPSCoR research project.

Research success of individual investigators as measured by:
Journal articles published or in press (does not include articles reported in 1st year progress report)

- Sevostianov, I. and Kachanov, M. On elastic stiffness and conductivity of contacting rough surfaces. *Mechanics of Meterials* **41** (2009), 375-384. (mentioned last year as submitted)
- Kushch, V.I., Shmegera, S.V., and Sevostianov, I. SIF statistics in micro cracked solids: effect of crack density, orientation and clustering. *International Journal of Engineering Science*, **47** (2009), 192-208.
- Kushch, V.I., Sevostianov, I., and Mishnaevsky, L. Effect of crack orientation statistics on effective stiffness of mircocracked solid. *International Journal of Solids and Structures* **46** (2009), 1574-1588.
- Kachanov, M., Mear, M.E., Rungamornrat J., and Sevostianov, I. Resistances of non-flat cracks, and their relation to crack compliances, *International Journal of Engineering Science* **47** (2009), 754-766.
- Guerrero, F., Sevostianov, I., and Giraud, A. On an arbitrarily oriented crack in a transversely-isotropic medium. *International Journal of Fracture* **153** (2008), 169-176.

- Sevostianov, I**.,** Kachanov, M., and Zohdi, T. On computation of the compliance and stiffness contribution tensors of inhomogeneities, *International Journal of Solids and Structures* **45** (2008) 4375-4383.
- Sevostianov, I. and Kachanov, M. Incremental compliance and resistance of contacts and contact clusters: implications of the cross-property connection. *International Journal of Engineering Science* (in press).
- Argatov, I. and Sevostianov, I. On relations between geometries of microcontact clusters and their overall properties *International Journal of Engineering Science* (in press).

Journal articles submitted during the second year of the project

- Sevostianov, I. Incremental elastic compliance and electric resistance of a cylinder with partial loss in the cross-sectional area (under review).

Conference Papers submitted and accepted

- E. Kutelia, S. Bakhtiyarov, O. Tsurtsumia, A. Bakhtiyarov, B. Eristavi, 2009, "The Thermally Activated Self-Healing of Cracks in Heterogeneous Architectured Metal/Metal/Ceramic High Temperature Coating Systems", **2nd International Conference on Self-Healing Materials**, Chicago, IL, June 28-July 1, 2009.
- 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 (accepted).
- Al-Shudeifat, M. A., E. A. Butcher, and T. D. Burton, "Comparison of Order Reduction Methodologies and Identification of NNMs in Structural Dynamic Systems with Isolated Nonlinearities," Proc. 27th International Modal Analysis Conference, Orlando, FL, Feb. 9-12, 2009.
- Al-Shudeifat, M. and E. A. Butcher, "Identification of the Critical Crack Depths and Locations of Rotordynamic Systems in Backward Whirl," 7th International Workshop on Structural Health Monitoring, Sep. 7-11, 2009, Stanford, CA.
- I.Sevostianov and V Kushch Effect of pore clusters on the statistics of peak stress and overall properties of porous material, SES 2008, October 12-15, 2008, Urbana-Champagne, IL.
- Incremental Compliance and Resistance of Contacts on a Rough Interface: Implications of the Crossproperty Connection, The 2009 Joint ASME-ASCE-SES Conference on Mechanics of Materials, June 24-27, 2009, Blacksburg, VA.
- I.Sevostianov Effect of Clusters of Microcracks and Pores on the Statistics of Peak Stress and Overall Properties of Porous/Microcracked Material, The 2009 Joint ASME-ASCE-SES Conference on Mechanics of Materials, June 24-27, 2009, Blacksburg, VA.
- I.Sevostianov Cross-property connections for materials with microstructure, Advanced Problems in Mechanics – 2009, June 30-July 5, 2009, St Petersburg, Russia.
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Conference papers submitted during the 2nd year of the project

- E. R. Kutelia, O. O. Tsurtsumia and S. I. Bakhtiyarov, 2007, "Investigation of Beilby Layer and Its Role in the Formation of Functional Surfaces on Fe-Cr-Al-La Alloys",

Proceedings, **The International Conference BALTTRIB 2007**, Kaunas, Lithuania, November 21-23, 2007, pp. 134-139.

Patents: none

Follow-on grant proposals submitted/funded including funding amounts during the 2nd year of the project

- Co-PI: Sayavur Bakhtiyarov **"A Model for Participatory, Collaborative STEM Learning", CCRAA** Grant with Amarillo College, TX, Department of Education Total: $3,242,767; NMT: 1,498,709; Mechanical Engineering Department at NMT: $487,000 (submitted and awarded)
- PI: Sayavur Bakhtiyarov NASA "**Center for Intelligent and Self-Repairing Aerospace Structures",** MUREP Group 5 University Research Centers Program. Joint proposal with NMSU, UNM, NMT, NNMC, LANL and SNL. $5,000,000 for 5 years, September 1, 2009 – August 31, 2014 (submitted).
- PI: Eric Butcher "**An Integrated Framework for Order Reduction, Robust Control and Real-Time Dynamic Substructuring of Nonlinear Multi-Scale Hybrid Aerospace Systems",** DOD $513,385 May 8, 2009 – May 7, 2012 (submitted and awarded).
- PI: Thomas Burton **"Center for Modeling, Sumulation, and Validation (MSV) in the Aerospace Science",** NASA Group 4 URC, $5,000,000 (submitted and not awarded).
- PI: Andrei Zagrai **"Embedded Ultrasonics for Structural Monitoring of Space Applications",** AFRL, Kirtland AFB, $199,999 for four years (submitted and awarded).
- PI: S. Lim **"DHS Homeland Security Science, Technology, Engineering and Mathematic Career Development: New Mexico Tech Explosives Engineering HS-STEM Program",** Department of Homeland Security (DHS), $400,000 for two years (submitted and awarded).
- PI: Andrei Zagrai **"Ultrasonic Assessment of Microstructure in Aerospace Materials",** WP AFRL, $25,000 student funding for one year (submitted).
- PI: Andrei Zagrai **"Intelligent Structural System for National Security Applications",** Los Alamos National Laboratories (LANL), $100,000 for one year (submitted and not awarded).
- PI: S. Lim **"An Investigation of the In-Direct Air Blast Control Technique Based on Atmospheric Conditions",** Office of Surface Mining, $150,268 for one year (submitted and not awarded).

Improvements in jurisdiction research and development infrastructure

- NMSU: Development of an experimental facility for vibration based health monitoring is in progress. We have also initiated development of a fatigue testing facility that will enable experimental study of distributed micro-damage. To date the NMSU research has mainly involved modeling, theory, and simulation. The new experimental facilities, when operational in Year 3, will significantly improve NMSU's capabilities in SHM and DP.

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:

- Self-Healing Materials Workshop**,** BOEING, Seattle, WA, January 20-21, 2009.
- *See final paragraph in "Progress on Objective 1*: Dr. Butcher and PhD student M. Shudeifat have collaborated for the past year 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:

- In the area of nonlinear ultrasonics, NMT researchers have been interacting with Dr. George Baaklini, Director of Optical Instrumentation & NDE Branch at NASA Glenn Center.
- 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
- An NMSU federal initiative based on this collaboration was a priority earmark item for FY 2010.
- Note: Increased involvement with NASA personnel is a priority for Year 3.

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. This NASA EPSCoR project will be one of only a few research projects featured in a presentation to the NMSU Board of Regents at the end of July, 2009.

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

(*The following paragraph also appears above*.) The NMSU AE undergraduate program is being strengthened by a grant from New Mexico SpaceGrant to one of the EPSCoR coPI's (Eric Butcher). The purpose of this grant is 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.

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
  - 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
  - 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) – white/male
  - Julie Mercer (MS graduate student funded by NASA EPSCoR grant) – white/female
  - Krystal Deines (MS graduate student funded by NASA EPSCoR grant) – white/female
  - Marcus Cramer (MS graduate student funded by NASA EPSCoR grant) – white/male
  - Ivan Argatov (postdoctoral 2009 funded by Los Alamos MOI 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 Year 3	
Milestone	**Year 3**
Basic research in four areas	**********
Design validation experiments	**
Conduct validation experiments	**********
Integrated multi-scale methodology development	**********
Methodology validation	**********
Deliverable: validated methodology	**********
NASA panel evaluations	**********
Statewide/NASA joint research	**********
IGERT proposal	*******