REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-11-2004

2. REPORT TYPE
Final Technical

3. DATES COVERED *(From - To)*
12-01-2000 – 02-29-2004

4. TITLE AND SUBTITLE

Magnetostrictive Particulate Composites for Damping

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-01-1-0037

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Greg P. Carman
Geoff McKnight, Pavel Chaplya, and Nersesse Nersessian

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Regents of the University of California, Los Angeles
University of California, Los Angeles
10920 Wilshire Boulevard, Suite 1200
Los Angeles, CA 90024-1406

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

USDAF Office of Scientific Research
4015 Wilson Boulevard, Rm 713
Arlington, VA 22203-1954

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The objective of this research effort was to develop a new passive smart damping material applicable to a wide range of aerospace structures. We believe that this innovative damping technology is defining a new standard for the field, based primarily on the research conducted under this grant. The novel damping approach absorbs energy using domain wall/detwinning concepts dependent upon stress amplitude and independent of vibrational frequency. This new approach was dramatically different than either viscoelastic materials that are frequency dependent and thermally limited or active approaches that require power supplies and external control electronics. As shown in Figure 1 (from Brodt and Lakes), the new materials investigated at UCLA had both large stiffness and large tan δ, unlike traditional materials that either had high stiffness with low tan δ (e.g metals or graphite epoxy composites) or low stiffness with high tan δ (e.g. elastomers). The research conducted under this grant helped the scientific community understand some basic physical properties of a wide range of materials under varying thermal-mechanical-magnetic-electrical loading conditions. This research effort was designed to develop a fundamental understanding for these new smart materials.

15. SUBJECT TERMS
damping, stiffness, composite, piezoelectric, magnetostrictive, shape memory

16. SECURITY CLASSIFICATION OF: unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Greg P. Carman
a. REPORT unclassified	**b. ABSTRACT** unclassified	**c. THIS PAGE** unclassified	unlimited	11	**19b. TELEPHONE NUMBER** *(include area code)* 310-825-6030

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
11 OCT 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Magnetostrictive Particulate Composites for Damping	**F49620-01-1-0037**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Regents of the University of California, Los Angeles, 10920 Wilshire Blvd., Suite 1200, Los Angeles, CA 90024-1406**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**11**	

Magnetostrictive Particulate Composites for Damping
F49620-01-1-0037

Greg P. Carman, Principal Investigator
Geoff Mcknight, Pavel Chaplya, and Nersesse Nersessian
Mechanical and Aerospace Engineering Department
University of California, Los Angeles
Los Angeles, CA 90095-1597
Voice: 310-825-6030
Fax: 310-206-2302
carman@seas.ucla.edu

INTRODUCTION

The objective of this research effort was to develop a new passive smart damping material applicable to a wide range of aerospace structures. We believe that this innovative damping technology is defining a new standard for the field, based primarily on the research conducted under this grant. The novel damping approach absorbs energy using domain wall/detwinning concepts dependent upon stress amplitude and independent of vibrational frequency. This new approach was dramatically different than either viscoelastic materials that are frequency dependent and thermally limited or active approaches that require power supplies and external control electronics. As shown in Figure 1 (from Brodt and Lakes), the new materials investigated at UCLA had both large stiffness and large tan δ, unlike traditional materials that either had high stiffness with low tan δ (e.g metals or graphite epoxy composites) or low stiffness with high tan δ (e.g. elastomers). The research conducted under this grant helped the scientific community understand some basic physical properties of a wide range of materials under varying thermal-mechanical-magnetic-electrical loading conditions. This research effort was designed to develop a fundamental understanding for these new smart materials.

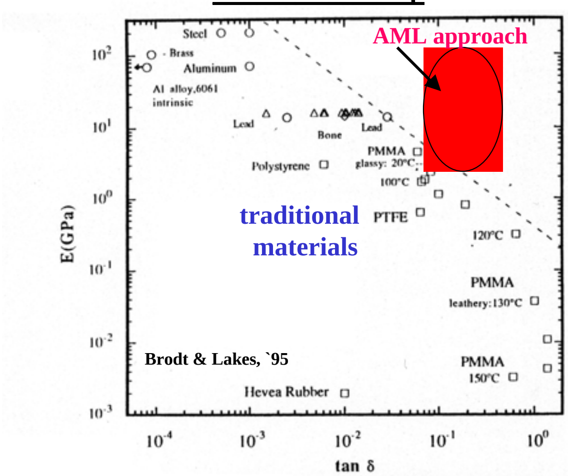
SUMMARY OF PROGRAM

During this research effort UCLA Active materials lab studieD three classes of material systems, ferromagnetic, ferroelectric, and ferroelastic. Initially in the program the focus was on determining the damping properties of the magnetostrictive composites (i.e. ferromagnetic) studied at UCLA. This work produced composites that had relatively high tan delta values and the stiffness values could be tailored for individual applications. As the program progressed, UCLA began to study the piezoelectric (i.e. ferroelectric) materials for damping using a similar philosophy to the magnetostrictive composites. The results demonstrated that tan delta for the ferroelectrics were considerably higher than the values for magnetostrictive composite systems. The explanation for relatively higher values was attributed to the "hard" nature of the piezoelectric studied while the magnetostrictive materials studied were of the soft category (i.e. small magnetic anisotropy). The research suggested that other magnetostrictive materials exist to provide substantially larger tan delta than measured initially in this program. This claim was substantiated during the final months of the program. Additionally, in the final year of the program, we focused on understanding damping in thin film systems for possible use in air force bunker buster bombs. This work studied the class of ferroelastic and ferromagnetic coupled field materials. Once again, we found that the amount of energy absorbed, or tan delta, was substantially larger for this class of materials when compared to either the magnetostrictive composites or to the piezoelectric material systems.

During this research effort, commercialization efforts were initiated by transferring technology to a small business named Fortis Technologies. Fortis is currently applying magnetostrictive composites to increase the fatigue life of engine turbine blades in a navy supported SBIR program. In addition to this technology transfer, UCLA worked with another small business CSA under a separate SBIR to apply the technology to vibration suppression during launch. CSA is also investigating other commercial opportunities for this technology, with a focus on sporting good applications. UCLA is also interacting with Eglin Air Force Base munitions division to evaluate several thin film damping concepts for MicroElectroMechanicalSystems (MEMS) components under high g loading. Therefore, the AFOSR grant has led to the transition of some fundamental research efforts into several commercial and defense applications.

In the following sections, we briefly describe an overview of the research activities on this grant. The description focuses mainly on the ferroelectric damping and the ferroelastic damping efforts. During the course of this research five journal articles were presented, three conference articles were presented, 2nd place student best paper SPIE was awarded, and the PI was elected to grade of ASME fellow. The PI was also awarded the prestigious Adaptive Structures and Material Systems Prize from ASME in 2004 and invited to present at the National Academy of Engineers Frontier of Engineering Symposium in 2004. In addition to this, the research supported two US citizens (Mcknight & Chaplys) toward their PhD and partially supported the work of a third US citizen (Nersessian). A summary of the articles published, the awards won, and the participants involved is provided at the end of this document.

Stiffness Loss Map



Traditional Approaches

- **Passive**
  - Visco-elastic Materials
    - Thermal limitations
    - Low stiffness
  - Shunting Circuit
    - Low energy absorption
- **Active**
  - Piezoelectric
    - Complexity/Integration
    - Weight

Figure 1: Stiffness loss map reproduced from Brodt and Lakes showing traditional materials along with the new active material lab (AML) approach.

REVIEW OF EFFORT

During this program we focused on ferromagnetic (e.g. magnetostrictive composites), ferroelectric (e.g. piezoelectric), and ferroelastic materials (e.g. shape memory alloys). A brief summary of a portion of the experimental data gathered is presented in Figure 2. In each figure a plot of the stress level to initiate domain wall motion (begin damping) and the stress level to complete domain wall motion is presented as a function of the relative field. The stress levels define the damping regime. Each point on the figures represents a separate test mechanical loading/unloading scenario. In Figure 2a the relative field for piezoelectric materials is electric field, in figure 2b the relative field is magnetic field, and in Figure 3c the relative field is temperature. In general we found that each class of active/smart materials displayed similar macro-scale damping behavior despite the differences in the intrinsic processes (i.e., polarization, magnetization, and phase/twin variant composition). The interesting feature we discovered was the difference in activation energies from one class of materials to another, in fact forming a continuum of opportunities. For example when reviewing Figures 2a-2c one observes that magnetostrictive material damping is active in the 2-12 MPa regime, piezoelectric material damping is active in the 15-100 MPa regime, and shape memory alloys are active in the 150-1000 MPa regime. Therefore, each material provides damping over specific stress regimes that span from low stress (2MPa) up to high stress (1GPa). This provides the opportunity to tailor the material to the application and also generate hybrid material systems for spanning several decades of stress.

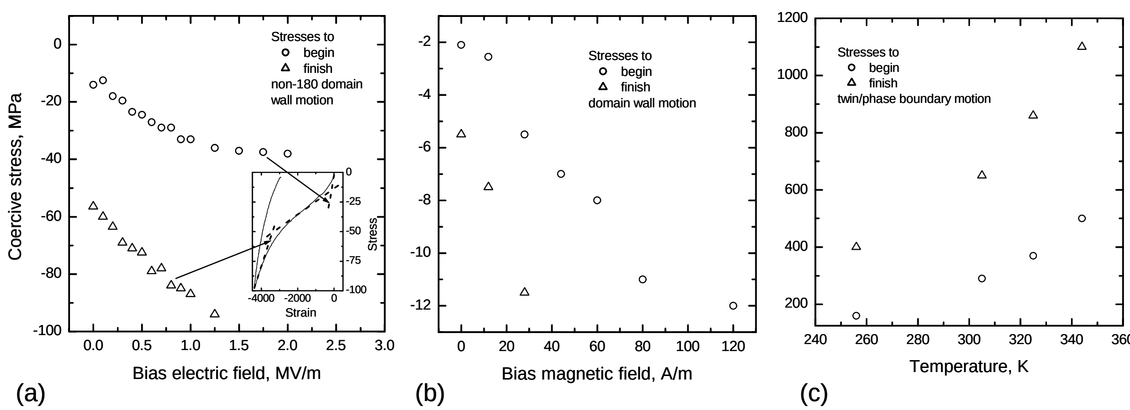


Figure 2: Critical stresses to begin and end strain jump in (a) piezoelectric; (b) magnetostrictive; (c) shape memory materials.

While a large portion of the research focused on experimentally evaluating the damping properties of various active (ferroelectric, ferromagnetic, and ferroelastic) materials, a portion of the work developed new models that could predict the damping properties. Once the experimental data was understood, we used a unified volume fraction concept to explain the active materials' macroscopic deformation in an attempt to predict damping properties. That is, the deformation of piezoelectric material is described in terms of the volume fraction of ferroelectric domains with polarization parallel or orthogonal to the applied load; the deformation of magnetostrictive materials is described in terms of the volume fraction of magnetic domains with magnetization parallel or orthogonal to the applied load; and the deformation of shape memory material is described in terms of the volume fraction of twin variants that are oriented favorably to the applied load.

To describe the unified approach we focused primarily on piezoelectrics. However the analytical development is sufficiently general to apply to the other classes of active materials, i.e. magnetostrictive and shape memory alloy. In general we postulated that the material's deformation and the amount of energy absorbed are directly proportional to the volume fraction of the domains undergoing non-180^o switching and the difference in electrical and mechanical domain wall pressures. The model allows peak-to-peak strain changes (or modulus) to be calculated under various stress amplitude and bias field conditions. Good agreement has been obtained between analytical and experimental data as can be seen in Figure 3.

In Figure 3 we plot predictions of total strain induced at three different stress levels under an applied field. Both analytical results and experimental results are presented in the figure for piezoelectric materials. The amount of damping is proportional to the change in strain with larger delta strain producing larger damping. The figure shows as the electric field initially increases, the total strain increases (i.e. damping) for all cases with the exception of the low stress level (25MPa). The 25 MPa stress level is at or near the critical energy to rotate domains. For the other two loading scenarios, 50 and 100 MPa, the strain increases because the domains are being initially oriented by the electric field but the mechanical load is sufficient to rotate them back to their original configuration. At a critical electric field value, the delta strain reaches a critical value, above which it begins to decrease. At this critical point the mechanical energy begins to be insufficient to rotate the domains back to the original direction and the total strain begins to decrease. In practice it is desirable to operate at or near this maximum value. As the electric field continues to increase to large values, the total strain decreases to zero, or the damping vanishes.

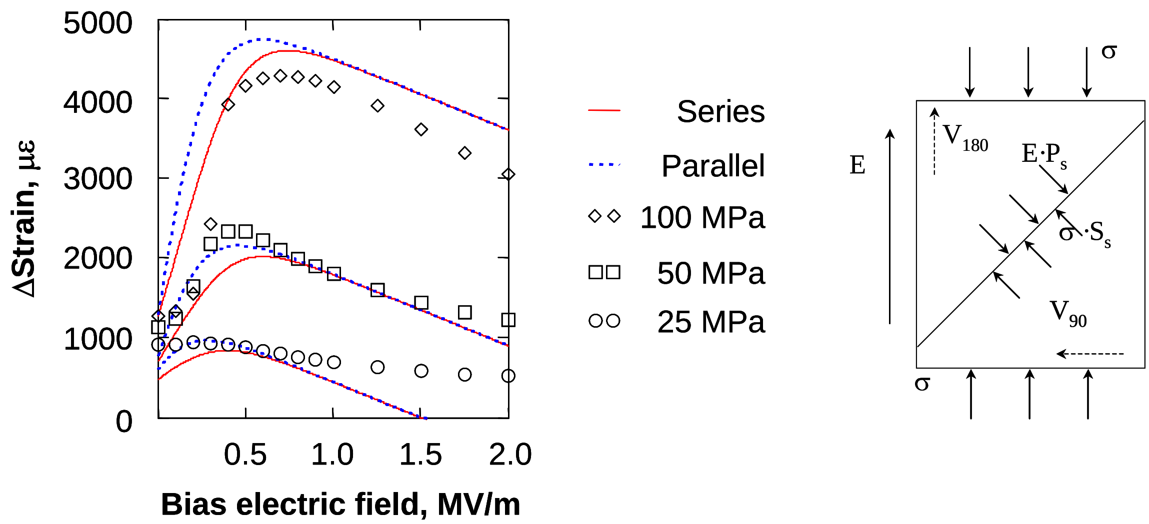


Figure 3: Analytical and experimental data for total compressive strain as a function of bias electric field.

During the final years of the program we expanded our effort to investigate a variety of new ferromagnetic materials. These include, but were not limited to, compositions similar to Terfenol-D but with higher Terbium content and polycrystalline NiMnGa. The NiMnGa system is a ferromagnetic shape memory alloy discovered in the 1990's. The higher Terbium content magnetostrictive materials were rejected for actuator applications in the 60's due to the relatively larger magnetic anisotropy (i.e. becoming a hard ferromagnetic). However, the large anisotropy is attractive for use in damping applications.

In the higher Terbium Terfenol-D compositions studied, the addition of Terbium provides larger magnetic anisotropy when compared to Terfenol-D. This larger anisotropy requires larger stresses to reorient the domain structure and absorbs larger amounts of energy. Experimentally we found a significant increase in damping properties (e.g. energy absorbed) and results suggest other materials would increase damping properties further (i.e. system non-optimized). In Figure 4, a sample test result reveals the significant increase in energy absorbed as a function of increasing Terbium content for 40% composite samples. Terfenol-D is the bottom diamonds in the figure 4 (Tb=0.3). As one can see increasing the terbium content from 0.3 up to 0.5 (triangles in figure) increases the amount of energy absorbed by almost a factor of two at zero bias magnetic field. In addition to Terfenol-D composite compositions, NiMnGa composites were also tested. In these samples twin boundary motion is the mechanism for damping. We discovered that this material also produced considerable damping when compared with other conventional material systems. However, all of these tests were conducted on single crystal samples. A manuscript is currently being written on the NiMnGa test data.

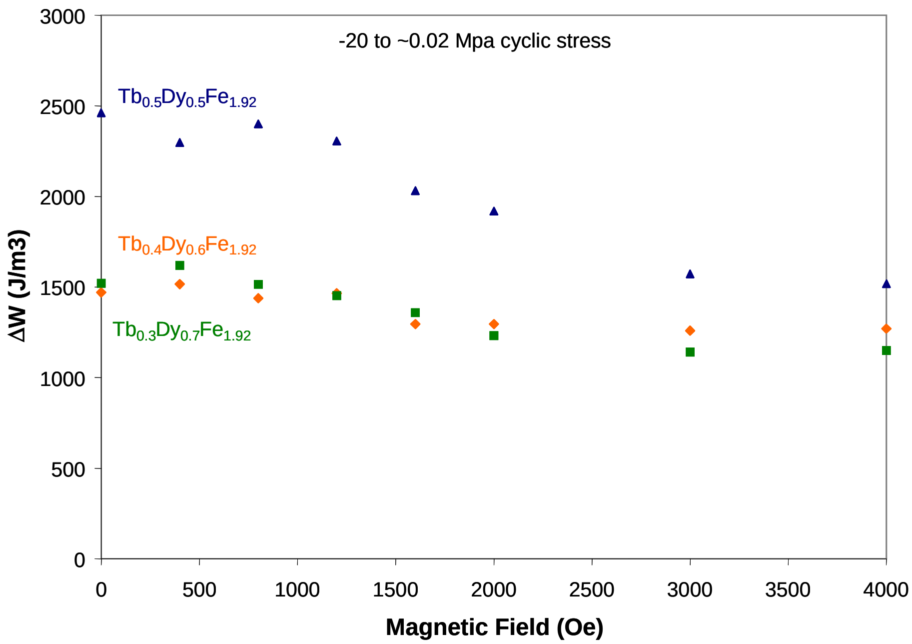
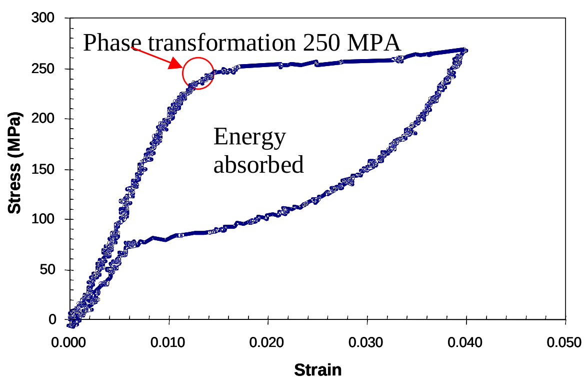


Figure 4: Energy absorbed in 40% composite samples under cyclic stress at different magnetic bias fields. .

In addition to testing monolithic and composite bulk samples, we investigated the damping properties of active thin films for use in MEMS structures. Defense applications include but are not limited to phase shifters in on the move antennas, accelerometers in bunker buster bombs, and inertial guidance systems in artillery shells. The material studied under this contract included thin film NiTi and also helped initiate a study into NiMnGa thin films. To produce the appropriate NiTi pseudoelastic film it took considerable processing efforts. That is, the films were manufactured at UCLA in their unique sputtering system and only a specific heat treatment produced films with pseudoelastic behavior. All the pseudoelastic films studied exhibit a stress induced phase transformation from austenite to martensite.

An example mechanical test result is shown in Figure 5 for the NiTi thin film post-processed at 600C for 1 hour. In figure 5 right is a photograph of the test system used to evaluate the properties of the film. For this particular thin film, it is austenite when the film is initially loaded. As the mechanical load increases up to 250 MPA, there is a knee in the curve representing the phase transformation from austenite to martensite. Upon unloading the path is hysteretic and responsible for absorbing energy. At a load of approximately 60 MPa the material reverts from the martensite phase back to the austenite phase. For this particular NiTi thin film, tan δ approaches 0.8 and stiffness values on the order of 60 GPa were measured. When these results are plotted on Figure 1, it falls in the far upper right hand portion of the figure.

NiTi thin film



MTS Test System

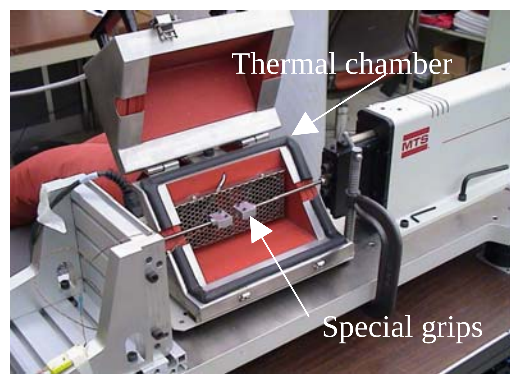


Figure 5: Energy absorbed in thin film NiTi with post-processing along with test setup.

Accomplishments/New findings

During this program we studied the relationship between three classes of active materials (ferroelectric, ferromagnetic, and ferroelastic) and passive damping. This included magnetostrictive composite systems, piezoelectrics, shape memory alloys, thin film shape memory alloys, and ferromagnetic shape memory alloys. Results provided a fundamental understanding of the physical process involved in damping. Using this understanding we developed some basic models to predict the materials damping response. Results of this effort have been transferred to several companies and an ongoing collaboration with an Air Force Research Lab. The work has been published in five journal articles and three conference proceedings, one conference paper won the 2nd best student paper competition. The PI was also elected to grade of fellow in ASME. "The Fellow Grade is the highest elected grade of membership within ASME, the attainment of which recognizes exceptional engineering achievements and contributions to the engineering profession." In 2004, the Adaptive Structures and Material Systems committee of the American Society of Mechanical Engineers awarded the PI the Adaptive Structures and Material Systems prize. This annual award is the highest recognition given in the field of Active Materials and honors an individual's "contributions to smart materials and structures and life long commitment to" this field. Finally, during 2004, the National Academy of Engineers invited the PI to present his research activities at their 10th annual "Frontier of Engineering" symposium. The symposium, with only fourteen presentations, invited "eighty-six of the nation's brightest young engineers" to participate.

PUBLICATIONS

Chaplya, P. and Carman, G.P., "Compression of Piezoelectric Ceramic at Constant Electric Field: Energy Absorption through non-180 Domain Wall Motion," Journal of Applied Physics, V. 92, no.3, page 1504-1507.

Nersessian, N., Or, S.W., Carman, G.P., Choe, W., and Radousky, H., "Hollow and Solid Spherical Magnetostrictive Particulate Composites," Journal of Applied Physics, V 96, num 5, pp. 3362-3365.

Chaplya, P. M. and Carman, G. P., "Dielectric And Piezoelectric Response Of Lead Zirconate-Lead Titanate At High Electric And Mechanical Loads In Terms Of Non-180 Domain Wall Motion," *Journal of Applied Physics*, Nov. 15, 2001, V. 90, Issue 10, pp. 5278-5286

Nersessian, N., Or, S.W., and Carman, G.P., "Magnetoelectric Laminates of Terfenol-D Composite & Lead Zirconate Titanate Ceramic Laminates," IEEE Transactions of Magnetics, V 40, no 4, July 2004. pp 2646-2648.

Mcknight, G. and Carman G.P., "Oriented Terfenol-D Composites," Material Transactions, Vol.43 No.5 (2002) pp.1008-1014

Chaplya, P., Mcknight G., and Carman G.P., “Mechanical Deformation of Field Coupled Materials,” ASME IMECE 2002-39009, Adaptive Structures and Material Systems Symposium of Aerospace Division, page 1-7

Pulliam, W., Lee, D., Carman, G., and McKnight, G., "Thin-layer Magnetostrictive Composite thin Films for Turbomachinery" SPIE SMART Structures & Material 2003, 5054:360 – 37

Chaplya, P. M. and Carman, G. P., “Compression of PZT-5H piezoelectric ceramic at constant electric field: investigation of energy absorption mechanism,” *Proc. SPIE , Active Materials and Mechanics*, V4699, 2002, pp. 30-37.

PRESENTATIONS

The International Society for Optical Engineering (SPIE), Smart Structures and Materials Symposium, March 2003

The International Society for Optical Engineering (SPIE), Smart Structures and Materials Symposium, March 2002

ASME, Adaptive Structures and Material Systems Symposium, November 2002

ASME, Adaptive Structures and Material Systems Symposium, November 2001

National Academy of Engineering Frontiers on Engineering Symposium (14 presenters invited)

AWARDS/HONORS

Adaptive Structures and Material System Prize 2004 ASME Adaptive Structures Committee

2nd Place Best Student Paper Award, SPIE’s 9th International Symposium on Smart Structures and Materials, March 2002

Fellow of ASME March 2003

ASME Adaptive Structures and Material Systems Best Paper Award for the year 2001

Honorary Professor of Baoutou University China. March 2002

Participants

1. Geoffrey Mcknight – PhD
2. Pavel Chaplya – PhD
3. Limited support for Nersesse Nersessian PhD (graduates 2004)