**Interdisciplinary Basic Research in Smart Materials & Structures**

**Key contributions include the following:**

- The adaptation and specialization of multi-channel vibration control techniques based on the characteristic vibration disturbance

- Demonstrated the importance of using combinations of multi-channel controller formulations for transient and steady-state vibration disturbance suppression and rejection

(continued on reverse side)
• Developed a new Hybrid Active Control Formulation which incorporates combination of a Nonlinear-rate feedback scheme and the Filtered-x adaptive feedforward controller for transient and steady-state disturbance suppression and rejection

• Developed a novel model-independent Total Energy Absorption (TEA) active control scheme for active vibration control in structures with vibration response characterized by standing and propagating waveforms.

• Developed a new Dual Active Control Scheme which incorporates a fuzzy adaptive learning rate with the Filtered-x algorithm for separate/combined vibration and acoustic radiation reduction
FINAL REPORT

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6. AUTHORS OF REPORT: K. Craig, J. Wen, H. Tiersten, D. Lagoudas
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

K. Craig


J. Wen


H. Tiersten


"Elastic Analysis of the Transfer of Shearing Stress from Partially Electroded Piezoelectric

"Electroelastic Equation's Describing Slow Hysteresis in Polarized Ferroelectric Ceramic Plates,"
8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

K. Craig

Abu Islam, Ph.D., Mechanical Engineering, December 1994
K.O. Prakah-Asante, Ph.D., Mechanical Engineering, May 1995
Andrew Wright, Ph.D., Mechanical Engineering, August 1996
James Fairweather, Ph.D., Mechanical Engineering,

J. Wen

Declan Hughes, Ph.D. student, completed in 2/97
Padma Akella, Ph.D. student, completed in 10/97
Carrie Dickinson, Ph.D. student, completed in 11/97

H. Tiersten

Yan Sheng Zhou - Post Doctoral Research Associate
Ben Je Lwo - Research Assistant
Jia Shi Yang - Post Doctoral Research Associate
Lidu Huang - Research Assistant, Ph.D. 1997
9. REPORT OF INVENTIONS

10. BRIEF OUTLINE OF RESEARCH FINDINGS

K. Craig

1. Islam and Craig

- A model of piezoceramic materials embedded in composites has been developed that is
detailed enough to capture the essential dynamic response of the structure and also simple
so that it can be used for on-line control applications.

- Measurement of dynamic characteristics of a structure is potentially a very attractive
method of non-destructive testing, since the properties can be measured at one point of
the structure and are independent of position chosen.

- The use of active materials for system identification has been found advantageous since
the condition of the structure can be continuously monitored and by using an on-board
microprocessor, the sensor output can be continuously evaluated.

- It has been found that the presence of damage can be detected simply by noting the
changes in natural frequencies of the structure. Location and assessment of damage
severity requires that a neural network be trained with dynamic responses from a model of
the structure having damage in different locations and various sizes.

- For closely spaced input frequencies of the neural network, the uses of fuzzification
greatly improved the convergence and accuracy of the network.

- It is possible to use this approach to monitor the growth of damage by using a damaged
state as a baseline for measurement.

- Mitigation of damage by reduction of dynamic moments at the damage locations has been
proved feasible provided the actuators have enough control authority.

2. Prakah-Asante and Craig

- The objective of this research was the development of new and improved active control
methods for vibration and acoustic radiation minimization in structures using piezoelectric
materials as sensors and actuators. Disturbance minimization of over 20 dB were
achieved from real-time experimental implementation of active control methods
developed.

- Key contributions include the following:

  - The adaptation and specialization of multi-channel vibration control techniques
    based on the characteristic vibration disturbance
• Demonstrated the importance of using combinations of multi-channel controller formulations for transient and steady-state vibration disturbance suppression and rejection

• Developed a new Hybrid Active Control Formulation which incorporates combination of a Nonlinear-rate feedback scheme and the Filtered-x adaptive feedforward controller for transient and steady-state disturbance suppression and rejection

• Developed a novel model-independent Total Energy Absorption (TEA) active control scheme for active vibration control in structures with vibration response characterized by standing and propagating waveforms.

• Developed a new Dual Active Control Scheme which incorporates a fuzzy adaptive learning rate with the Filtered-x algorithm for separate/combined vibration and acoustic radiation reduction

3. Wright and Craig

• Discovered that convergence of LMS System Identification Algorithm in Active Sound Cancellation depends on the coherence between the test signal broadcast from the actuator and the error microphone. This coherence is degraded for low level test signals. However, when the power in the test signal exceeds the noise threshold, convergence is assured. Further increase in power results in no improvement and indeed degrades performance when echoes begin to interfere with the direct path.

• Formed some preliminary results regarding the time domain cepstral transform (TDCT) for dereverberating acoustic signals. This is intended to help the coherence described above for large test signals. Discovered that time delays can be found from the number of zero eigenvalues in the TDCT matrix.

• Developed a compact acoustic actuator using piezoelectric patches to excite resonances in a plate. This actuator was used to cancel sound. Its main drawback is that its response below 400 Hz was minimal, which is the primary area where ASC is needed. Further work needs to be invested in lowering the effective frequency response. Modeling and simulation to try out preliminary concepts should be pursued.

4. Fairweather and Craig

• Modeling approaches to the induced-strain actuation of structural systems presently lack methods of satisfactorily dealing with structures possessing complex boundaries, material anisotropy, and point mass loading. In addition, the most frequently employed models of induced-strain actuation, static equivalent-force models, have been shown in experimental studies to be poor predictors of both system resonant frequencies and the stress field in the induced-strain actuator.
A modeling approach based on the mechanical impedance of the host structure has been shown in the literature to accurately predict the measured dynamic behavior of several simple dynamic systems driven by induced-strain actuators. This research extends this impedance approach to more complex structures.

The present work centers on the use of the eigenvectors and eigenvalues extracted from finite-element-based normal-mode analysis to determine the mechanical impedance of the host structure. Such an approach extends the applicability of present impedance models to structures for which closed-form expressions of mechanical impedance do not exist.

Equations are developed to compute the mechanical impedance of the structure based on the finite element results. These impedances are employed to obtain the dynamic response of the previously studied cantilever beam and simply-supported plate structure. Comparisons of the predicted response are made with models published in the literature, including models incorporating analytically determined impedances. The predictions of the present approach demonstrate excellent agreement with the prior analytical impedance models.

Experiments are conducted for the purpose of beam model validation. Prior static equivalent-force models are shown incorrectly predict the first resonance of the driven beam system by nearly 20%, while the FEA-based impedance model is shown to be accurate to within 2.5%.

The FEA-based impedance model of the plate system is compared to experimental results published in the literature, and the new approach demonstrates excellent predictions of the system dynamic response when compared to the previous static equivalent-force approach.

The methods developed can be directly extended to complex structures, and a research plan centered on experimental verification of the approach is proposed to further the present work.

J. Wen

- Preisach model for hysteresis:
  We have applied the Preisach model for the hysteresis found in piezoelectric materials and shape memory alloys. We have demonstrated experimentally that this physically motivated phenomenological model applies well to piezoceramic materials and adequately to SMA. The Preisach model is amenable to efficient identification as well as to direct inversion. We have demonstrated output following through direct cancellation of the hysteretic effect in both PZT and SMA.

- Passivity based control:
We have shown that PZT voltage and collocated strain rate form a passive pair which can be used for robust closed loop feedback control. However, under sample-and-hold implementation, the strain rate measurement and high bandwidth of the PZT device causes a large artificial noise. We have extended the passive feedback scheme to include collocated strain feedback (which is not passive with respect to the voltage input) and other noncollocated sensor feedback. A linear matrix inequality approach is used to synthesize an "optimal" passive output based on the available sensors which can be in turn used in existing passive feedback strategies.

• Near and Far Effects:
We have successfully explained the so-called "Near and Far Effect" observed in piezoceramics. Basically, existing models predict well the transfer function from PZT to strain gauge when they are far apart, but poorly when they are very close. We use a input-dependent modal expansion to better approximate the solution of the governing partial differential equation.

• Feedback Control of SMA:
We have demonstrated that the dynamic effect in shape memory is not negligible especially when it is connected with a flexible host structure. Based on a simplified model that we have developed (Shu, Lagoudas, and Wen), we can prove closed loop stability for SMA force control when SMA is connected with a rigid surface, and predict (and have experimentally observed) instability when SMA is connected to a flexible beam. We have developed both fixed gain and adaptive control schemes that can achieve closed loop stability by using the beam strain feedback. In the case of adaptive control, steady state error can be removed with no model information required. It is also observed that sampling significantly affects the amplitude of the steady state oscillation.

H. Tiersten

- Non-dissipative electroelastic equations for fully electroded actuators subject to large electric fields were obtained from existing general recoverable nonlinear, rotationally invariant, electroelastic equations. The equations, which contain only one component of electric field, are for fully electroded actuators only. The equations for the thin stress-free polarized ferroelectric ceramic plate subject to large electric fields were shown to account for existing experimental data for the case of positive increments in electric field only.

- On account of the restrictions mentioned for actuators, two-dimensional non-dissipative electroelastic plate equations for both unelectroded and electroded portions of actuators were derived. These equations are linear in the deformation and nonlinear in the electric fields. The equations hold for thicker actuators because flexure was included in the description as well as extension.

- Laminated composite plates forced into cylindrical bending by fully electroded actuators were treated using both approximate plate equations and those of linear elasticity. The
results obtained from the two approaches were compared and it was shown that for large span length-to-thickness ratios the agreement is quite good but for small ones it is not good at all. In addition, the plate solution indicates that the shearing force between the actuator and the composite plate is transferred as a delta function at the edge of the actuator, while the linear elastic solution shows that the actual distribution is transferred near the edge and becomes singular at the edge.

- Non-dissipative two-dimensional equations describing the flexure of symmetric laminated composite plates with partially electroded actuators attached were derived and applied to the problem of the cylindrical bending of the plate due to voltages applied to the actuators. The plate solution revealed that even when the electrodes end a very short distance from the edge of the actuators, the shearing stress transferred is non-singular.

- Since the approximate plate equations tend to be inaccurate for the calculation of the transfer of horizontal shearing stress in the case of cylindrical flexure discussed in the preceding paragraph, a linear elastic analysis of that problem was performed. The calculations performed using the accurate linear elastic analysis revealed that the maximum shearing stress is less than $1/10$ of that obtained from the plate equations and extends over a distance 10 times as large. This distance, however, is still quite small so that the edges of the electrodes can be quite close to the edge of the actuator and still have the shearing stress small at the edge.

- Existing rotationally invariant electroelastic equations were extended to include the simplest mechanical and electrical viscous type dissipation. The nonlinear description obtained satisfies the principle of material objectivity. In the absence of thermal considerations the description reduces to seven equations in seven dependent variables. In the linear version for the polarized ferroelectric ceramic, the electrical dissipative variable contains the spin tensor because of the residual polarization. If the electric field is used as the independent thermodynamic variable instead of the polarization, which was used, the resulting objective description reduces to four equations in four dependent variables. In the linear limit for the polarized ferroelectric ceramic the electric variable does not contain the spin tensor because there is no biasing electric field. In the application to actuators both systems reduce further because of the condition of plane stress.

- It has been shown that for thin wide beams forced by actuators on the surfaces, the expression commonly used for the applied moment should be reduced by the factor $(1-v)$, where $v$ is the planar Poisson's ratio for the plate. This is directly analogous to the reduction of the plate elastic constant to the beam elastic constant and arises for the same reason.

- The rotationally invariant equations of recoverable nonlinear electroelasticity have been extended to account for irreversible slow hysteresis effects, which occur when polarized ferroelectric ceramics are driven by large electric fields. The extension is accomplished by the use of internal variables so that the description is consistent with thermodynamics. All material irreversibility is taken to be a consequence of the polarization electric field
irreversibility. Since the residual polarization is in the fixed thickness direction, only one internal variable was required. Since we were concerned with the slowest possible hysteresis, we ignored the resulting evolution equation and took the known irreversible thickness polarization-electric field saturation curve as the starting curve. Since the residual polarization at zero electric field is always the starting point, the description was readily extended from the saturation loop to narrower major hysteresis loops by means of reasoning motivated by domain switching. After the general nonlinear three-dimensional equations were obtained, they were reduced to linear strain and plane-stress because all experimental data available was from strain measurements on a thin wide beam forced by voltages applied to very thin polarized ferroelectric ceramic actuators on the surfaces. On account of this the equation for the thin wide beam with irreversible actuators attached was derived. The resulting equation was used in the calculations for comparison with experiment. The new irreversible material coefficients were obtained from data on one major hysteresis loop along with the coefficients in the saturation polarization - electric field relation. These then known coefficients were used to calculate other hysteresis loops, which were shown to agree quite well with measurements. It was also shown that proper control of the time at which the driving voltage was switched off could significantly increase the lifetime of an actuator by reducing the amount of depoling in an operation.
A. Research Accomplishments

A generic form of Gibbs free energy for polycrystalline Shape Memory Alloys (SMAs) has been developed, by forming the increments of both elastic potential energy and Gibbs chemical energy over a Representative Volume Element (RVE) with respect to an infinitesimal increment of martensite. The initial material heterogeneity of SMAs, which is essential for the initiation of the phase transformation, was modeled by connecting the reference Gibbs energy with a probability distribution function. In Part I of a three-part paper, the theoretical derivations are presented. Specific cases of the thermomechanical response of SMAs predicted by the model are presented in Part II, together with experimental results for phase transformation at constant plastic strains. Experimental results and model predictions for cyclic loading of SMAs with evolving plastic strains are considered in Part III of a trilogy on SMAs.

A series of experiments performed on NiTi SMA wires undergoing thermally induced cyclic phase transformation under constant applied load was utilized for model simulations and subsequent comparisons with model predictions. Using the present model, thermally induced phase transformations under varying magnitude of applied load can be modeled for both untrained and trained SMAs. Finally, an application of the model to stress induced phase transformation in thin SMA specimens, where transformation strain localization occurs, has been explored. Part III of this trilogy on SMAs studies the evolution of plastic strains accumulating in thermally induced cyclic phase transformation under constant applied load, therefore fully characterizing the thermomechanical response of SMAs under undergoing multiple operating cycles.

Experimental results of the cyclic thermally induced phase transformation under constant applied load have been investigated. It has been observed that the accumulation of plastic strains continues beyond a large number of cycles (2,000), while TWSM is saturated and remains stable after 100 to 300 transformation cycles, depending on the magnitude of the applied load. Motivated by the experimental observations, and based on the general framework established in the first two parts of this series of three papers on SMAs (Bo and Lagoudas, 1997, Lagoudas and
Bo, 1997), evolution equations for the accumulation of plastic strains and plasticity related back and drag stresses, which govern the evolution of TWSM, have been proposed. Finally, model predictions are compared with experimental data, and a procedure for the determination of material constants has been described. Combined with the formulation developed in Parts I and II, the cyclic thermomechanical response of SMAs can be fully characterized using the proposed model.

A connection between the Preisach hysteresis model and the above thermomechanical model has also been investigated. The memory (wiping out) property for the present model is determined in a way similar to that of the Preisach model. Comparisons between the present model predictions and the experimental results show that the present model accurately predicts the minor loop hysteresis response of SMAs, even when such minor loops are close to the transformation start and finish points. Compared with the Preisach model, the present hysteresis model follows a thermodynamic formulation, which makes it easier to account for the effects of changing loading paths and two-way memory effect induced by cyclic loading. The developed numerical implementation algorithm can also be incorporated easily in conjunction with other existing thermomechanical constitutive models, thus providing a general scheme for the modeling of hysteretic response of SMAs, based on physical parameters.

Finally, an adaptive control methodology for identification and compensation for a class of hysteresis models employed for the representation of active materials has been implemented. A theoretical framework has been derived that establishes the well-posedness of a nonlinear identification formulation for characterizing a class of static hysteresis phenomena in a class of actuators associated with smart materials, where conditions have been derived that guarantee the convergence of Galerkin approximations for the Krasnosel'skii-Pokrovskii (KP) integral hysteresis operator. A linearly parametrized form of the KP integral operator, suitable for gradient adaptive control, that provides numerical examples of adaptive identification from a constitutive law that characterizes a class of SMA actuators undergoing thermomechanical actuating paths, has been derived and implemented.

B. Highlights of Key Research Accomplishments

1. Devised a constitutive model for cyclic loading of SMA actuators and used it for shape control of active trailing edge flaps.
2. Devised a training procedure for SMA actuators and used it to condition actuators for active composites.
3. Implemented an Active Flap Deployment System for BVI control.
4. Developed a shape and tracking control algorithm for an active beam with SMA actuators using nonlinear hysteretic control algorithms.
5. Designed and tested an active elastomeric composite damper with SMA particles.
6. Developed the theory of Active Flexible Rods with embedded SMA actuators.
7. Established a connection between Preisach hysteresis models used for control with micromechanics based models of polycrystalline SMA.
8. Demonstrated the connection between thermal, mechanical and structural coupling in active structures with SMA actuators.
9. Modeled the behavior of hybrid active plates composed of piezoelectric and SMA layers.
10. Implemented using layerwise FEM the structural response of active composite laminates with SMA layers.

C. Examples of technology transfer

1. The main interaction with industry that we had on SMA was Bell Helicopter (Warren Young), which independently funded a project on elastomeric damper stabilization by utilizing SMA particles.
2. We have (Texas A&M U.) a CRDA with the Army Vehicle Structures Directorate at Langley (Kevin O’Brien). We plan periodic visits to Langley to exchange technical information.
3. We have (Texas A&M U.) a CRDA with the Naval Air Warfare Center (David Barrett). We used this CRDA to have access to SMA particles that we embedded in elastomeric dampers for the Bell Helicopter project.
4. We started working with the Naval Surface Warfare Center in Annapolis (we are currently negotiating a project to be initiated in the summer of 97), where we will use our established technology on active flaps with SMA actuators developed under ARO funding, to study the similar problem for a hydrofoil. The Navy will give us seed funding to carry out an initial feasibility study with Othon Rediniotis, and we hope to make progress in that area within the next year with the support of David Winyard.
5. We are currently working with Othon on a STTR (phase I), funded by ONR, where we are trying to implement some of the ideas of SMA actuated flexible structures for underwater vehicles and mimic the motion of biological systems.
6. There is extensive cooperation with Martin Marietta (Bernie Carpenter). We are planning to use data from the active flap they built for the smart wing program to validate our own simulations, both on modeling the actuation and the control strategies implemented.
7. Recently there is an exchange of technical information and genuine interest from Northrop Grumman (Peter Jardine). Northrop Grumman is interested in our SMA FEM model to be used in the design of the torque tube actuators, which will be used in the second phase of the smart wing project.
8. Our main materials supplier and supporter with technical information and data all these years is Dr. M. Schetky from Memry Corporation. He is providing us with SMA torque tube actuators, to be tested in our facilities. In return we share data and our findings under the ARO program.
9. Boeing has also expressed an interest in our SMA model and we have provided copies of our papers and our Fortran code to them (Dean Jacot).
10. There is a technical exchange with laboratires abroad, especially France and Russia. With the ARO European office fundind the proposal of Prof. Volkov, this cooperation will reach a point where we could have joint students and publish jointly papers. In addition, I have evaluated and recently asked to monitor a large project on SMA coupling devices funded by congress in Russia, to redirect Russian scientists from military to civilian research (International Science and Technology Center- (ISTC) project N 294). I hope that we can influence the Russian scientists to start research activities relevant to US interests.

Our numerical implementation of Shape Memory Alloy actuators is being used by NRL in the design of the second phase smart wing for Northrop Grumman. According to Virginia DeGiorgi from NRL, who is working on the design of the smart wing, our numerical
implementation is currently the only one available capable of 3-D computations, which are necessary for the torque tube actuators used in the smart wing. The development of this software was supported by the ARO URI on smart materials at RPI/Texas A&M, as a result of several years of basic research on the model development and then the implementation phase.

2. Mostly due to my publication record on work funded by ARO during the past five years, I have recently been selected as one of 15 young scientists from a nationwide search by the institute for defense analyses (ida). The institute seeks nominations mainly from universities and every two years forms a group of 15 promising scientists below the age of 40 from all disciplines (engineering and sciences). I was honored to be selected this year to serve in this panel for the next two years and visit the different DOD facilities, Pentagon, State Department and other strategic agencies related to DOD. The objective of this panel is to make aware the participating scientists of trends in the new technologies vital for the security of the country.

D. HONORS AND AWARDS

Who's Who in America, 1995-
Who's Who in Science and Engineering, 1996-
TEES Senior Research Fellow, 1997.
E. Student Thesis Supervision

UNDERGRADUATE (the following list includes only students who wrote a research report; a much larger number of undergraduate students have participated in the research project over the years as workstudents or student technicians)

MASTERS
Graduated:
3. Abu Bakar Siddiq Qidwai, "Numerical Evaluation of the Constitutive Response of Shape Memory Alloys," 9/93-12/95
Matthew D. McNeese, "Fabrication of NiTi Shape Memory Alloy From Elemental Powders by Hot Isostatic Pressing," 7/94-12/97.

DOCTORAL
Graduated:
Gongming Xu, "Shape Control of Active Composites," 3/94-12/96 (co-chair).
Current:
David Miller, "Fabrication and Mechanical Characterization of Active Composites," 6/96-
Abu Bakar Siddiq Qidwai, "Finite Deformations in Shape Memory Alloys," 1/96-

POSTDOCTORAL
3. Declan Hughes, (jointly with Dr. Junkins) "Design of Mechanical and Control Experiments in Active Materials and Smart Structures," 1/96-12/96.
F. Publications

Refereed Journal Publications


Accepted Journal Publications


Submitted Journal Publications


Books

Chapter Contribution


Editor


Papers in Proceedings Volumes and Edited Books


