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13. ABSTRACT (Maximum 200 words)  This summarizes the findings of our effort to exploit the concept of programmable structures and related topics. Results indicate that modeling and control methods are extremely significant in the performance of such integrated structures. In addition results on model updating, eigenstructure assignment, smart rotor shaft control of critical speeds and a new nonlinear modal control algorithm have been developed.  <b>19950308 056</b>					
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## I. Summary of Results

### *Programmable Structures*

The goal of this project was to examine the feasibility of a programmable structure concept for vibration suppression and damage detection. A programmable structure is defined as a subset of smart materials that consists of a host structure with embedded sensors, actuators and surface mounted control module. The specific objectives of this effort were the fabrication, modeling, control and experimental verification of a programmable structure system. In particular, the issues of modeling that emerged as significant are the importance of including internal passive damping mechanisms, the significance of modeling local change in elastic modulus of the actuator/sensor system and the failure of standard finite element and modal analysis methods to produce experimentally verified results that are capable of reproducing transient time responses. It is apparent that internal damping mechanisms for layered beam elements must be modeled, (e.g., strain rate damping) as must the modulus of the embedded sensors and actuators. If these effects are not included, theoretical predictions and measured responses do not agree. These results are reported in the papers listed in section 2.

It is also significant to note that the electronic control module is so light and small that the equations of motion for vibration are not altered by the addition of a surface mounted control module. The control law used in a given application, however, is extremely significant in improving vibration response. For example, in free decay, the damping ratios of the first several modes of the closed loop system can vary by as much as a factor of five depending on the choice of control law. The improvement over open loop response offers an order of magnitude decrease in settling time illustrating very strong vibration suppression.

Results in diagnostics using a programmable structure concept offer a unique ability for self diagnostics of structural systems. Small, local changes in mass and stiffness are known to be difficult to determine using frequency measurements. The programmable structure however has the ability to determine using frequency measurements. The programmable structure however has the ability to measure time difference over different time intervals. These time differences have been shown to illustrate the presence of damage.

Some progress has been made on the issue of optimal location and size of embedded piezoactuators in isotropic beam and plate structures using optimization methods. The optimal thickness ratio for host versus piezoceramic layer for a given modulus ratio has been quantified in design chart form as reported in Ashburn and Garcia and in Minas, Garcia and Howard.

### *Control Issues*

In addition, it was found that the control law most suited for use with programmable structures is an optimized positive position feedback controller. This control, invented by Fanson of JPL was modified by us by applying an optimal control technique to the choice of filter gains. Such a design, which is basically a compensator, leads to substantially improved performance over  $H_\infty$  control, LQR control, PID control and standard positive position feedback (PPF). The reason PPF and its modifications provide superior control over the other methods have to do with its inherent stability. Closed loop stability of a PPF depends only on knowledge of the open loop natural frequencies. Open loop control frequencies are one of the best known and predicted physical quantities available. Hence the design is fairly robust to model error.

## II. Smart Rotating Machine Shafts

As an off shoot of the planned research, the feasibility of suppressing critical speeds in rotating machinery by using embedded shape memory alloys and a stiffness scheduling open loop control algorithm was studied. Preliminary results show that in certain circumstances, such a scheme can in fact remove critical speed deflection from rotating machines during start up and run down.

Shape memory alloys have been generally dismissed for use in transient control applications because of their long response time. The spinning up of rotating machinery however represent a vibration suppression problem occurring over a finite time period. A simplified model of dynamic analysis of a flexible shaft disc system is used and combined with a spin up profile resulting in a system with time varying coefficients. A stiffness scheduling control algorithm, defined as adopting the stiffness of the shaft to reduce disturbance sensitivity is developed. An embedded shape memory alloy is used to actuate the rotor shaft system between two different elastic moduli. As the rotating shaft starts from zero and ramps up to its operating speed the stiffness is switched using the shape memory alloy as the shaft runs through the critical speed, effectively reducing the shaft deflection.

The current model is used to numerical simulate the results of using the embedded shape memory alloy to perform the stiffness control task using a 4th order Runge-Kutta method for three cases. The three cases illustrate a comparison between low stiffness, high stiffness and stiffness switched during ramping, the results, illustrated graphically in the following shows that stiffness scheduling substantially reduces the amplitude response during ramp up through critical speed. The control of critical speeds in rotating machines by an open loop system with embedded shape memory alloys present the possibility to improve the

performance of rotating machines in a broad class of industrial and military applications where start up critical speed problems currently exist. The proposed method also allows for on line adjustment over time providing a guard against field problems such as fatigue.

### III. Model Updating and Control Results

In an attempt to match our finite element models to the experimental response data in the form of modal data we came upon several linear algebra results which provided systematic ways for analytical finite element models to be adjusted to agree with measured data. Because our model correction matrices are similar to gain matrices of pole placement and eigenstructure assignment we also have obtained rather interesting results in control theory.

Eigenstructure assignment is a popular and well studied method of feedback control. The majority of eigenstructure assignment methods are formulated in state space. However, the motivation for using eigenstructure assignment for vibration control comes from a designers statement of required performance in terms of modal information - i.e., natural frequencies, damping ratios and mode shapes. In particular, mode shape information is stated in a physical coordinate system rather than in the state space. Hence a new eigenstructure assignment algorithm is developed in a second order physical coordinate system using a theory developed for solving second order inverse eigenvalue problems. This approach is developed by realizing that the model updating, or model correction, problem associated with adjusting finite element models using experimental data is closely related to the eigenstructure assignment problem of control theory. Thus the theoretical development proposed here sets a background for developing many new eigenstructure assignment algorithms.

Several important features result from eigenstructure assignment gains calculated from inverse theory. First, the computational algorithm runs in about 1/3 the time of direct eigen-

structure assignment yet produces identical gains. Secondly, the inverse approach retains those natural frequencies and mode shapes of the original open loop system not assigned by the algorithm. This prevents the common difficulty of shifting the desired modes to acceptable performance levels, whilst the unassigned open loop eigenstructure shifts to some undesirable values (potentially unstable) spoiling the closed loop performance.

#### IV. Nonlinear Modal Control Method

This work extends previous work on nonlinear normal modes to include the case of forced response. This allows the nonlinear normal mode method to be applied to the feedback control problem providing a new method of controlling nonlinear multiple degree of freedom systems. The proposed method uses a transformation proposed earlier for homogeneous systems written in state space form. The coordinate transformation for the forcing vector is defined here in state space and related to the physical coordinate system. The result is a pseudo modal decoupling transformation of a nonlinear inhomogeneous system. Although interesting in its own statement, this transformation also provides a nonlinear modal control scheme. This result is applied to a known coupled two degree of freedom oscillator with a cubic stiffness term. The results illustrate the design of a nonlinear modal control law.

The invariant manifold method has been extended to the forced response case and now includes the output equation as well as the state equation. The appropriate transformations have been derived and applied to a two degree of freedom nonlinear oscillator illustrating that a successful feedback control law can be designed for a nonlinear system based on nonlinear modal control techniques. In addition, several new definitions have been put forth to allow nonlinear mode nomenclature to more precisely agree with the non-conservative linear nomenclature.



## V. List of 1994 Manuscripts

Inman, D. J., "Computer Simulation and Nomographs," *The Engineering Handbook*, ed. R. C. Dorf, CRC Press, Boca Raton, Florida, 1995, to appear.

Inman, D. J. and Atalla, M. J., "Calculating Natural Frequency Mode Shapes and Time Responses," *Shock and Vibration Computer Program*, ed. W. D. Pilkey, Shock and Vibration Information Analysis Center, to appear.

Lam, M. and Inman, D. J., "Symmetric Pole Placement for Mechanical Structures," *ASME Journal of Dynamic Systems, Measurement and Control*, revised November 1994.

Parker, G. and Inman, D. J., "Linearization and Control of Nonlinear Systems," *IEE International Journal of Control*, submitted October 1994.

Parker, G. and Inman, D. J., "Decentralized Sliding Mode Control of Nonlinear Robots," submitted to the *Journal of Intelligent and Robotic Systems - Theory and Applications*, submitted October 1994.

Parker, G. and Inman, D. J., "Model Following Control of Time-Varying Systems Represented by 2nd Order Matrix Equations," *International Journal of Control*, submitted October 1994.

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Ben-Haim, Y. and Inman, D. J., "Vibration Control with Unknown Disturbances Represented by Convex Models of Uncertainty," *Journal of Dynamic Systems, Measurement and Control*, submitted April 1993.

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*Journal of Sound and Vibration*, to appear.

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Banks, H. T., Wang, Y., and Inman, D. J., "Bending and Shear Damping in Beams: Frequency Domain Estimation Techniques," *Journal of Vibration and Acoustics*, Vol. 116, No. 2, pp. 188-197, April 1994.

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Holcomb, M. D., Inman, D. J. and Pokines, B. J., "Active Vibration Isolation Device," 1994 North American Conference on Smart Structures and Materials, *Passive Damping*, ed. C. R. Johnson, Vol. 2193, pp. 325-335.

## VI. Scientific Personnel Supported

William Saunders, PhD  
Marca Lam, PhD candidate  
Donald J. Leo, PhD candidate  
Eric Austin, PhD candidate  
Brett Pokines, PhD candidate  
Daniel J. Inman, PhD, principle investigator  
Ephrahim Garcia, PhD, principle investigator