This document summarizes the research accomplished under the support of AFOSR-85-0220 from the period of July 1, 1985 to June 30, 1988. Results obtained during this period under AFOSR support are briefly described in the first section. This section is followed by listings of books published, papers published, proceedings published, degrees granted and lectures given while the PI was under Air Force Support.
Introduction This document summarizes the research accomplished under the support of AFOSR-85-0220 from the period of July 1, 1985 to June 30, 1988. Results obtained during this period under AFOSR support are briefly described in the first section. This section is followed by listings of books published, papers published, proceedings published, degrees granted and lectures given while the PI was under Air Force Support.

Research Summaries Several results were obtained under the support of this grant which related to the distributed parameter, or partial differential equation, model of a flexible structure. The global model forming the thrust of this research is given by the set of partial differential equations

\[ u_t(x,t) + L_1 u_t(x,t) + L_2 u(x,t) = f(x,t) \]  

defined on some domain with the appropriate boundary and initial conditions. Here \( u(x,t) \) is an element in an appropriate space (usually a Hilbert space) and represents the physical displacement of a structure. \( L_1 \) and \( L_2 \) are partial differential operators of the spatial variable \( x \) in \( \mathbb{R}^3 \), \( t \) is the time and \( f(x,t) \) is a distributed (or point wise) loading function and/or control force. Finite dimensional approximations of this system are also considered. The general goal of the proposed work is to find properties of the solution of (1) as a function of the operators \( L_1 \) and \( L_2 \) or their approximations. The results discovered while examining this problem are summarized in the following.

First results for equation (1) in the circumstance that the coefficient operators of (1) are non-self-adjoint were obtained. It has been previously shown that certain non-self-adjoint operators arising in mechanics can be shown to be self-adjoint with respect to a particular self-adjoint operator. The work here extends and formalizes this approach to include systems with velocity dependent damping. This extension follows the lumped parameter case presented earlier and places emphasis on the adjoint of eigenfunction for use in performing modal
analysis. This work also examines oscillatory behavior and stability results. In addition, certain control results can be stated for such systems, which indicates the suitability of using finite dimensional approximation. These results are also delineated in the previous two interim reports (Nov. 3, 1986 and October 5, 1987).

Another major area of research has been the quantifying of the degree of coupling in eigenfunction expansion of (1) caused by the existence of so called non proportional damping. This occurs when the operators $L_1$ and $L_2$ in (1) do not commute on an appropriate domain. In this case, a standard eigenfunction expansion of the solution results as an infinite set of coupled ordinary differential equations. The procedure developed here uses approximating decoupled equations containing a coupling index. This index allows for both a rational approximation of (1) by finite dimensional decoupled modal like equations and a characterization of the degree of coupling. A formal presentation of these results are forthcoming. Finite dimensional versions are published in Bellos and Inman (1988).

In addition, a research area addressed during this time period is the modeling of system such as (1) when the physical parameters of the system under consideration are also temperature dependent. Such models yield coupled structural and heat equations and produce unstable systems. These effects have been observed in space and have in fact caused catastrophic failures. The results obtain here yield a coupled set of partial differential equations which are delineated in Wan, Cozzarelli and Inman (1988) and provide a prediction of such failures. A control algorithm for such systems is discussed in Wan (1986).

Several significant results for finite dimensional systems were also developed under the support of this grant. Briefly they are

1. An eigenstructure assignment methodology is adopted to the identification problem for a finite dimensional model of (1), such as a finite element approximation providing an ability to match experimental data with an analytical model. The gains in the eigenstructure assignment procedure are treated as adjustments to FEM damping and stiffness matrices. Results are detailed in Minas and Inman (1988), and forms the first systematic approach to matching finite element modes with experimental data.

2. A sufficient condition for the stability of a conservative gyroscopic system has been derived. This condition yields new regions in parameter space for stable operation of
gyroscopic systems including gyroscopes. It includes and extends regions defined by previously published results. The details and examples are given in Inman (1989).

3. The nature of the interaction between a structure, a control law, and the actuator used to implement the control law on a system consisting of a cantilevered composite beam and a proof-mass actuator is considered. This interaction is found to be potentially destabilizing especially if the structural model is particularly flexible. These results are delineated in Zimmerman and Inman (1988). The choice of actuator break frequency relative to the lowest structural frequency is critical.

Books Edited and Authored  During the award period, the principal investigator authored one text (to appear November 21, 1988) and co-edited one research monograph. They are:


Journal Papers Published  The following lists papers that have been submitted to archival journals for review, have been accepted for publication or are in print during the award period.


Conference Papers and Proceedings The following is a list of papers presented at conferences and published in the conference proceedings as a full paper during the award period.


Invited Conference Lectures The following invited lectures at conferences were given during the award period (in addition to the lectures implied by the conference papers cited above.


**Invited Institutional Lectures** The following lists invited lectures given at academic institutions, industries and government laboratories by the principal investigator during the award period.


**Editorships** During the award period of this grant the principal investigator served as an associate editor for four research journals. They are:

- Associate Editor of ASME Journal of Vibration, Acoustics, Stress and Reliability in Design (1986-89)
- Associate Editor of ASME Journal of Applied Mechanics (1988-91)
- Associate Editor of Mechanics of Machines and Structures (1986-89)
- Associate Editor of International Journal of Analytical and Experimental Modal Analysis

**Organizational Activities** During this award period the principal investigator organized several workshops, and technical meetings. They are:

- American Society of Mechanical Engineers, Executive Committee Buffalo
  Organizer of Session on Structural Control for the 1987 Design Conference, Boston, MA. Associate Editor, Journal of Vibration, Acoustics, Stress and Reliability in Design (1986-89)
- Society of Engineering Science
  Organized Session on Dynamics for the 22nd Annual Technical Conference, August 1985
- Conference Chairperson and Organizer for the 23rd Annual Technical Meeting, August 1986
- Chairperson and Organizer for the 4th Air Force Office of Scientific Research Forum on Large Space Structures, August 1986

**Graduate Degrees Supervised** The following students received the indicated degree with the advisement principal investigator during the award period. In addition, two post doctoral supervision and current students are listed.


Tylock, James, "Noise Control Experiments," August 1985 (MS) (joint with A. Soom).

Shen, Hue-Min, "Identifying the Damping Matrix from Modal Data," August 1985 (MS).


Zimmerman, David, "Low Authority Control of Large Space Structures with a Constrained Threshold Control Formulation," June 1987 (PhD).
Yae, Kwang, "Reduced Order Modeling and Analytical Model Improvement for Structural Dynamics and Control," July 1987 (PhD).
Bellos, John, "Vibrations of Non-Proportionally Damped Structures," October 1987 (MS).

Post Doctoral Research Associates
Liang, Zhong, PhD, SUNYAB 1987, working on experimental structural control.

Current Doctoral Candidates

Current Master Candidates
Johnson, Dexter, PhD, expected 1991.
Martinez, Greselda, PhD, expected 1991.
Korpanthy, Daniel, MS, expected 1989.

References