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Final Scientific Report

for

Qualitative Results for Distributed Parameter Systems
 (AFOSR - 85 - 0220)
 01 July 1985 to 30 June 1988

by

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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

$$u_{tt}(x,t) + L_1 u_x(x,t) + L_2 u(x,t) = f(x,t) \tag{1}$$

defined on some domain Ω 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 \mathcal{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

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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:

Inman, D.J., Vibrations: Control, Measurement and Stability, Prentice Hall, Englewood Cliffs, New Jersey, 1989.

Inman, D.J. and Simonis, J.C. ed., Vibration Control and Active Vibration Suppression. ASME DE Vol. 3, 1987.

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.

1. Inman, D.J., "Resonance Avoidance in Nonnormal Mode Lumped Mass Structures and Machines," in review.
2. Minas, C. and Inman, D.J., "Matching Finite Element Models to Modal Data," ASME Journal of Vibrations, Acoustics, Stress and Reliability in Design, to appear.
3. Yae, H. and Inman, D.J., "Model Reduction in a Subset of the Original States," in review.
4. Zimmerman, D.C., and Inman, D.J., "On the Nature of Interactions Between Structures and Actuators," AIAA Journal of Guidance, Control and Dynamics, to appear.
5. Liang, Z. and Inman, D.J., "Rank Decomposition Methods in Modal Analysis," ASME Journal of Vibration, Acoustics, Stress and Reliability in Design, to appear.
6. Inman, D.J., "A Sufficient Condition for the Stability of Conservative Gyroscopic Systems," ASME Journal of Applied Mechanics, to appear.
7. Oshman, Y., Inman, D.J. and Laub, A.J., "Square Root State Estimation for Second-Order Large Space Structure Models," AIAA Journal of Guidance, Control and Dynamics, to appear.

8. Zimmerman, D.C., Inman, D.J. and Juang, J-N, "Vibration Suppression Using a Constrained Rate-Feedback Threshold Control Strategy," *AIAA Journal of Guidance, Control and Dynamics*, to appear.
9. Bellos, J. and Inman, D.J., "The Nature of Coupling in Nonconservative Lumped Parameter Systems," *AIAA Journal of Guidance, Control and Dynamics*, to appear.
10. Ross, A.D.S. and Inman, D.J., "On Resonance of Lumped Mass Damped Linear Systems with Normal Modes," *ASME Journal of Vibration, Acoustics, Stress and Reliability in Design*, to appear.
11. Cudney, H.H. and Inman, D.J., "Control Formulation for Flexible Structures Using Physical Coordinates," *Mechanics of Structures and Machines*, to appear.
12. Wan, K.T., Cozzarelli, F.A. and Inman, D.J., "Thermal Runaway Due to Strain-Heating Feedback," *AIAA Journal*, Vol. 26, No. 5, 1988.
13. Zimmerman, D.C., Horner, G.C. and Inman, D.J., "Microprocessor Controlled Force Actuator," *AIAA Journal of Guidance Control and Dynamics*, Vol. 11, No. 3, May-June, 1988, pp. 230-236.
14. Inman, D. J. and Olsen, C.L., "Dynamics of Symmetrizable Nonconservative Systems," *ASME Journal of Applied Mechanics*, Vol. 55, No. 1, March 1988, pp. 206-212.
15. Yae, K. and Inman, D.J., "Response Bounds for Linear Underdamped Systems," *ASME Journal of Applied Mechanics*, Vol. 54, No. 2, 1987, pp. 419-423.
16. Inman, D.J. and Jiang, B.L., "On Damping Ratios for Multiple Degree of Freedom Linear Systems," *International Journal of Analytical and Experimental Modal Analysis*, Vol. 2, January 1987, pp. 38-42.
17. Ahmadian, M. and Inman, D.J., "Some Stability Results for General Linear Lumped-Parameter Dynamic Systems," *ASME Journal of Applied Mechanics*, Vol. 53, No. 1, 1986, pp 10-15.

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.

1. Mook, D.J. and Inman, D.J., "An Experimental and Numerical Investigation of the Robustness of System Identification Techniques," *Proceedings of the International Conference on Computational Engineering Science*, Vol. 2, April 1988, pp. 64 .iv1-64 .iv4.
2. Mayne, R.W. and Inman, D.J., "Prospects of Damping Structures via Actuator Interaction," *Proceedings of the International Conference on Computational Engineering Science*, Vol. 2, April 1988, pp. -44.vi1 - 44.vi4.
3. Oshman, Y. and Inman, D.J., "Optimal On-Line Measurement System Configuration Strategies," *Proceedings of the 29th Structures, Dynamics and Materials Conference*, Vol. 2, April 1988, pp. 1048-1049.

4. Ross, A.D.S. and Inman, D.J., "On Resonance of Lumped Mass Damped Linear Systems," *Proceedings of the 6th International Modal Analysis Conference*, Vol. 1, February 1988, pp. 42-48.
5. Liang, Z. and Inman, D.J., "On Rank Decomposition Methods for Modal Analysis," *Proceedings of the 6th International Modal Analysis Conference*, Vol. 2, February 1988, pp. 1176-1179.
6. Garcia, E., Inman, D.J. and Horner, G.C., "System Identification in the Microcomputer Environment," *Proceedings of the 6th International Modal Analysis Conference*, Vol. 2, February 1988, pp. 1596-1601.
7. Minas, C. and Inman, D.J., "Correcting Finite Element Models with Measured Modal Data Using Eigenstructure Assignment Methods," *Proceedings of the 6th International Modal Analysis Conference*, Vol. 2, February 1988, pp. 583-587.
8. Bellos, J. and Inman, D.J., "Lumped Systems with Non Proportional Damping," *Proceedings of the 6th International Modal Analysis Conference*, Vol. 2, February 1988 pp. 876-882.
9. Zimmerman, D.C., Inman, D.J. and Juang, J-N., "Low Authority-Threshold Control for Large Flexible Structures," *Proceedings of the 29th Structures, Dynamic and Materials Conference*, Vol. 2, April 1988, pp. 459-469.
10. Banks, H.T., Wang, Y., Inman, D.J. and Cudney, H.H., "Parameter Identification Techniques for the Estimation of Damping in Flexible Structure Experiments," *Proceedings of the 26th IEEE Conference on Decision and Control*, December 1987, Vol. 2, pp. 1392-1395.
11. Inman, D.J. and Zimmerman, D.C., "Actuator Issues in Controlling Flexible Structures," to appear in the *Second NASA/DOD Control Structures Interaction Technology AFWAL-TR-88-3052*, June 1988, pp. 376-388.
12. Oshman, Y. and Inman, D.J., "Square Root State Estimator for Large Space Structures," *Proceedings of the AIAA Guidance, Navigation and Control Conference*, August 1987, Vol. 1, pp. 617-627.
13. Zimmerman, D.C., Inman, D.J. and Juang, J-N, "Threshold Control Technique for Large Flexible Structures," *Proceedings of the 28th Structures, Structural Dynamics and Materials Conference*, April 1987, pp. 125-134.
14. Oshman, Y. and Inman, D.J., "Square Root Filtering for Continuous-Time Models of Large Flexible Structures," to appear in the *Proceedings of the 6th VPI & SU/AIAA Symposium on Dynamics and Control of Large Structures*, June 1987.
15. Liang, Z. and Inman, D.J., "A Time Domain Method for Global Damping Measurement and Modal Analysis," *Proceedings of the 5th International Modal Analysis Conference*, April 1987.
16. Zimmerman, D.C., Horner, G.H. and Inman, D.J., "Microprocessor Controlled Force Actuator," *Proceedings of 27th Structures, Dynamics and Materials Conference*, May 1986, pp. 243-251.

17. Liang, Z., Gao, Q. and Inman, D.J., "On Phase and Modal Parameter Measurement for Large Structures," Proceedings of the 4th International Modal Analysis Conference, February 1986, Vol. II, pp. 993-999.
18. Inman, D.J. and Jha, S.K., "Identification of the Damping Matrix for Tires," Proceedings of the 4th International Modal Analysis Conference, February 1986, Vol. II, pp. 1078-1080.
19. Inman, D.J., "Control of Symmetrizable Distributed Parameter Systems," Proceedings of the 24th IEEE Conference on Decision and Control, December 1985, Vol. II, pp. 729-731.
20. Inman, D.J., "Modal Control of Symmetrizable Structures," Structural Control, Proceedings of the 2nd International Symposium, July 1985, H.H.E. Leipholz, ed. Martinus Nijhoff Publishers, 1987, pp. 321-342.
21. Ahmadian, M. and Inman, D.J., "Closed Loop Stability of Large Space Structures with Reduced Order Controllers," Proceedings of the 5th VPI & SU Symposium Dynamics and Control of Large Structures, July 1985, pp 275-290.
22. Cudney, H.C., Inman, D.J. and Horner, G.C., "Vibration Control of Flexible Beams Using an Active Hinge," Proceedings of the 5th VPI & SU Symposium Dynamics and Control of Large Structures, July 1985, pp. 455-470.
23. Inman, D.J. and Hendrickson, W.L., "Identification of a Damping Matrix from Modal Data," Proceedings of the 5th VPI & SU Symposium Dynamics and Control of Large Structures, July 1985, pp. 19-26.

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.

1. "Experimental Modeling and Control of Distributed Mass Structures with Lumped Mass Actuators," Optimization Days, May 1988, Montreal, Quebec.
2. "Comments on Electromechanical Actuators for Controlling Flexible Structures," 5th AFOSR Forum on Space Structures, August 20, 1987, Monterey, California.
3. "Shock Loading of Large Flexible Space Structures," ASCE 1986 Annual Conference, October 1986, Boston, Massachusetts.
4. "Identification of a Damping Model in Cord Rubber Composites," International Symposium on Composite Materials and Structures, June 1986, Beijing, China.
5. "Oscillatory Non-Self-Adjoint Systems," 19th Midwest Mechanics Conference, Ohio State University, September 1985.
6. "On the Time Response of Multidegree of Freedom Second Order Systems," 22nd Annual Meeting of the Society of Engineering Science, University Park, Pennsylvania, October 1985.

7. "Dynamics and Control of Temperature Dependent Flexible Structures," AFOSR Third Forum on Large Space Structures, College Station, Texas, July 1985.

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

1. "Estimation of Damping Matrices," January 17, 1986, Harris Corporation, Government Systems Division.
2. "Modal Testing: State of the Art?" February 21, 1986, Brown University, Division of Applied Math.
3. "Research in Flexible Structures,:" April 3, 1986, Michigan State University, Systems Science Group.
4. "Dynamics and Control of Flexible Structures with Temperature Dependent Properties," June 25, 1986, Air Force Office of Scientific Research, Aerospace Sciences Program.
5. "Experimenting in Parameter Identification of Flexible Structures," Wright Patterson Air Force Base, October 27, 1986, Flight Dynamics Branch.
6. "State of the Art in PC Based Modal ID," Kistler Instrument Corporation, November 21, 1986.
7. "Modal Testing of Flexible Structures," Air Force Rocket Propulsion Laboratory, January 14, 1987.
8. "Testing of Damping Mechanisms in Flexible Structures," Air Force Weapons Laboratory, January 29, 1987.
9. "Model Reduction Methods in Physical Coordinates," June 10, 1987, NASA Langley Research Center.
10. "Model Testing for Mathematicians," June 23, 1987, SUNY/Brown University Workshop on Parameter Identification.
11. "On the Nature of the Interaction Between Structures, and Actuators," October 20, 1987 Howard University.
12. "Control Structure Interaction," November 20, 1987, University of Iowa, Department of Mechanical Engineering.
13. "Comparing Finite Element Models with Experimental Data," February 19, 1988, University of Florida at Gainesville, Department of Aerospace Engineering and Mechanics.
14. "Actuator Dynamics and Flexible Structures," February 24, 1988, Rutgers University, Department of Mechanical and Aerospace Engineering.
15. "The Effect of Actuator Dynamics in Structural Control," February 25, 1988, New Jersey Institute of Technology.

16. "Control Structure Interaction," April 25, 1988, University of Colorado Boulder, Center for Space Structures and Controls.
17. "Experiments for Control Structure Interaction," April 27, 1988, Center for Control Sciences, Brown University Division of Applied Mathematics.

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 Vibrations, Acoustics, Stress and Reliability in Design (1986-89)
 Society of Engineering Science
 Organized Session on Dynamics for the 22nd Annual Technical, October 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
 Chairperson and Organizer for the 2nd Air Force Office of Scientific Research Workshop on Control of Systems Governed by Partial Differential Equations, October 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.

Hendrickson, William, "Identification of a Damping Matrix for Composites," February 1985 (MS).
 Tylock, James, "Noise Control Experiments," August 1985 (MS) (joint with A. Soom).
 Shen, Hvue-Min, "Identifying the Damping Matrix from Modal Data," August 1985 (MS).
 Pong, Meau-Fu, "Effect of Complex Modes on Modal Testing," January 1986 (MS).
 Cudney, Harley, "Digital Control of a Beam with Joint," June 1986 (MS).
 Ebbing, David, "Damping in Composite Materials," August 1986 (MS).
 Wan, K.W., "Analysis and Control of Thermal Instabilities in Structural Components," September 1986, joint with Professor F. Cozzarelli (PhD).
 Cook, Pauline J., "Identifying Modal Data for Compressors," February 1987 (MS).
 Liang, Zhong, "On Modal Testing in the Time Domain," February 1987 (PhD).
 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).
Lochocki, Ronald F., "Digital Control of Flexible Structures - an Experimental Approach," August 1987 (MS).
Garcia, Ephraim, "System Identification in the Micro Computer Environment," August 1987 (MS).
Bellos, John, "Vibrations of Non-Proportionally Damped Structures," October 1987 (MS).
Lee-Glauser, Gina, "Experimental Verification of Eigensystem Realization Algorithm," January 1988 (MS).
Minas, Constantinos, "Modal Correction via Pole Placement Methods," January 1988 (MS).
Sheth, Upendra R., "Modal Cost Analysis for Model Reduction," December 1987 (MS).

Post Doctoral Research Associates

Oshman, Yaakov, D.Sc. Technion, Israel Institute of Technology, 1986, working on filtering problems for Large Space Structures, 1986-1987.
Liang, Zhong, PhD, SUNYAB 1987, working on experimental structural control.

Current Doctoral Candidates

Cudney, Harley, "Piezo Ceramics in Control of Flexible Structures," expected 1988.
Bellos, John, "Non-Normal Mode Combined Dynamical Systems," expected 1989.
Garcia, Ephraim, "Slewing Control of Flexible Structures," expected 1989.
Ross, A.D.S., "Truss Control" expected 1989.
Minas, Constantinos, "Identification of Flexible Structures," expected 1990.

Current Master Candidates

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

References

Inman, D.J., 1986, "Qualitative Results for Distributed Systems," 1986 Interim Scientific Report, AFOSR-85-0220.
Inman, D.J. 1987, "Qualitative Results for Distributed Systems," 1987 Interim Scientific Report AFOSAR-85-0220.
Bellos, J. and Inman, D.J., "The Nature of Coupling in Nonconservative Lumped Parameter Systems," AIAA Journal of Guidance, Control and Dynamics, to appear.
Wan, K.T., 1986, Analysis and Control of Thermal Instabilities in Structural Components," Ph.D. Dissertation, SUNYAB.
Minas, C. and Inman, D.J., "Matching Finite Element Models to Modal Data," ASME Journal of Vibrations, Acoustics, Stress and Reliability in Design, to appear.
Inman, D.J., "A Sufficient Condition for the Stability of Conservative Gyroscopic Systems," ASME Journal of Applied Mechanics, to appear.
Zimmerman, D.C., and Inman, D.J., "On the Nature of Interactions Between Structures and Actuators," AIAA Journal of Guidance, Control and Dynamics, to appear.