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Final Technical Report of AFOSR Grant 91-0097

"Stabilization and Control Problems in Structural Dynamics"

Report Period: January 1, 1991-December 31, 1993

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I. Review of Achievements and Progress

During the grant period January 1, 1991-December 31, 1993, Dr. G. Chen, the P.I., and Dr. J. Zhou, the co-P.I., along with graduate students and scientific collaborators, have studied various facets of analysis, optimization, stabilization and control problems in structural dynamics. The research results have been submitted to scientific journals and presented at professional meetings. Overall speaking, we have stayed closely in course of the planned directions. We are grateful to AFOSR for the kind assistance and generous support during this period. Let us summarize the achievements and progress below.

Twenty-six scientific publications supported by this grant are listed in §II. We have

- (i) 17 articles published (cf. *Papers in Print* in §II);
- (ii) 5 articles accepted or to appear (cf. *Papers Accepted or to Appear* in §II);
- (iii) 4 articles currently pending or in revision (cf. *Papers Submitted* in §II);
- (iv) 3 advanced books/monographs published (cf. *Books and Monographs* in §II).

In particular, the publication of three books authored by the PI's are the most significant publications of this period. Due to the comprehensive nature of those books, there are diverse contributions by the PI's in advancing the mathematical study of computation and analysis of distributed parameter systems. Our first book, entitled "Boundary Element Methods", constitutes a definitive mathematical account of boundary element methods first ever published, while the other two books entitled "Vibration and Damping in Distributed Systems, Vols. I and II" elucidates stability/stabilization, and enable the readership to visualize and understand resonance as never before.

Other major progress made by the PIs include

- (a) the development of boundary element methods and boundary stabilization for elastostatic and elastodynamic thin or shallow *shells*;
- (b) the numerical computation of the (nonstationary) Navier-Stokes equations by a combination of boundary element-particle method;
- (c) numerical analysis and computation of nonlinear elliptic equations by a boundary element-monotone iteration scheme.

We hope to carry on parts of the above research in the coming years. A new proposal,

entitled "Computation, Control, Optimization and Vibration Analysis of Shell equations", has been submitted to AFOSR and NSF for possible joint funding for the years 1994-96.

II. List of Publication

Papers in Print

- [1] G. Chen, S.A. Fulling, F.J. Narcowich and S. Sun, Exponential decay of energy of evolution equations with locally distributed damping, *SIAM J. Appl. Math.*, **51**, (1991) 266-301.
- [2] G. Chen and H.K. Wang, Asymptotic locations of eigenfrequencies of vibration of an Euler-Bernoulli beam with nonhomogeneous structural and viscous damping coefficients, *SIAM J. Control Opt.*, **29**, (1991) 347-367.
- [3] G. Chen, M.P. Coleman and J. Zhou, Analysis of vibrating eigenfrequencies of a thin plate by Keller-Rubinow's wave method (I), *SIAM J. Appl. Math.*, **51**, (1991) 967-983.
- [4] G. Chen and J. Zhou, The wave method for determining the asymptotic damping rates of eigenmodes I: The wave equation on a rectangular or circular domain, *SIAM J. Control Opt.*, **29** (1991) 656-677.
- [5] G. Chen and J. Zhou, Some boundary control problems and computations for the linear elastostatic Kirchhoff plate on an exterior domain, in "Boundary Control and Variations", Proc. of IFIP Workshop, J.P. Zolesio ed., Springer-Verlag Lecture Notes on Control and Information Science, #178, Springer-Verlag, New York, (1992) 82-117.
- [6] G. Tian and J. Zhou, Quasi-variational inequalities with non-compact sets, *J. Math. Anal. Appl.*, **16**, (1991) 583-595.
- [7] G. Tian and J. Zhou, The maximum theorem and the existence of equilibrium in abstract economies without lower semicontinuity, *J. Math. Anal. Appl.*, **166**, (1992) 361-364.
- [8] J. Zhou and G. Tian, Transfer method in characterizing the existence of maximal elements for binary relations on compact or noncompact sets, *SIAM J. Opt.*, **2**, (1992) 360-375.
- [9] G. Chen, Boundary element methods for elliptic boundary value problems, Lecture Notes published by the Institute of Applied Mathematics, National Tsing Hua Uni-

versity, Hsinchu, Taiwan, June 1991, (169 pages).

- [10] G. Chen, M.P. Coleman and J. Zhou, The equivalence between the wave propagation method and Bolotin's method in the asymptotic estimation of eigenfrequencies of a rectangular plate, *Wave Motion*, **16**, (1992) 285-297.
- [11] G. Chen, F. Huang and C.Y. Lin, More boundary energy dissipation does not necessarily imply larger asymptotic decay rates, *Asymptotic Analysis*, **6**, (1992) 191-203.
- [12] G. Chen and Q. Zheng, *N*-person differential games, Part II, *J. Computational Mathematics*, **10**, (1992) 303-320.
- [13] G. Chen, Q. Zheng, W.H. Mills and W.H. Shaw, *N*-person differential games, Part III, *J. Computational Mathematics*, **10**, (1992) 321-338.
- [14] G. Chen and S. Sun, Augmenting a Fredholm operator of zero index to achieve invertibility for elliptic boundary value problems, *J. Math. Anal. Appl.*, **176**, (1993) 24-48.
- [15] L. Ji and G. Chen, Point observation in linear-quadratic elliptic distributed control systems, in *Identification and Control of PDEs*, SIAM, Philadelphia, Chapter 11, (1993) 155-170.
- [16] G. Tian and J. Zhou, Quasi-variational inequalities without concavity, *J. Math. Anal. Appl.*, **171**, (1993) 289-299.
- [17] M.R. Baye, G. Tian and J. Zhou, Characterizations of the existence of equilibria in games with discontinuous and nonquasiconcave payoffs, *Review of Economic Studies*, **60**, (1993) 935-948.

Papers Accepted or to Appear

- [1] G. Chen, Zhou and R. McLean, Boundary element method for shape (domain) optimization of linear-quadratic elliptic boundary control problems, in *Proceedings of IFIP*, June 1992, Sophia-Antipolis.
- [2] G. Chen, P.J. Morris and J. Zhou, Visualization of special eigenmode shapes of a vibrating elliptical membrane, *SIAM Review*, to appear.
- [3] K. Viswanathan, P.J. Morris and G. Chen, Instability waves in supersonic jets in circular and noncircular ducts, *J. Sound & Vibration*, to appear.

- [4] J. Zhou, Extension of the Zorn lemma to general nontransitive binary relations, *J. Optimization Theory and Application*, **80**, (1994) 337-351.
- [5] G. Tian and J. Zhou, The transfer continuities, generalization of Weierstrass and maximum theorems: a full characterization approach, *J. Mathematical Economics*, (approximately 16 pages).

Papers Submitted

- [1] J. Zhou, On the existence of equilibrium for abstract economy, submitted in August, 1992 to *J. Math. Anal. Appl.*, (approximately 19 pages).
- [2] Z. Ding, L. Ji and J. Zhou, Constrained LQR problems in elliptic distributed control systems with point observations, submitted in August, 1993 to *SIAM J. Control Opt.*, (approximately 21 pages).
- [3] Z. Ding and J. Zhou, Constrained LQR problems governed by the potential equations on Lipschitz domains with point observations, submitted in November, 1993 to *J. de Mathematiques Pures et Appliquées*, (approximately 20 pages).
- [4] G. Chen and M. Pedersen, Regularities and pseudodifferential symbols of boundary layer operators for elastostatic thin plates and shells, Part I, submitted.

Books and Monographs

- [1] G. Chen and J. Zhou, *Boundary Element Methods*, Academic Press, London (1992).
- [2] G. Chen and J. Zhou, *Vibration and Damping in Distributed Systems, Vol. I: Analysis, Estimation, Attenuation, Design*, CRC Press, Boca Raton, Florida (1993).
- [3] G. Chen and J. Zhou, *Vibration and Damping in Distributed Systems, Vol. II: Visualization, Experimentation*, CRC Press, Boca Raton, Florida (1993).

III. Activities

Colloquium and Conference Talks

- 1. K. Viswanathan, P.J. Morris and G. Chen, 30 minute talk in the 30th Aerospace Sciences Meeting of AIAA, Reno, Nevada, January 1992.
- 2. G. Chen and J. Zhou, Invited talk, 1992 IFIP on "Boundary Control and Boundary Variation", Ecole des Mines, Sophia-Antipolis, (30 min. talk), June 1992.

3. G. Chen and J. Zhou, Invited talk, AMS-SIAM Summer Conference on Control and Identification of Partial Differential Equations, Mt. Holyoke College, S. Hadley, Massachusetts, (1 hour major talk), July 1992.
4. G. Chen and J. Zhou, 30 minute talk in the SIAM Conference on Control in the 90's Minneapolis, September 1992.
5. G. Chen, Invited colloquium, Math. Dept., Southern Methodist University, Dallas, January 1993.
6. G. Chen, One hour technical presentation, Air Force Wright Laboratory, Dayton, Ohio, February 1993.
7. G. Chen and J. Zhou, 30 minute talk in the Texas PDE Conference, College Station, TX, March 1993.
8. G. Chen, One hour pretalk for Frontiers Lecture Series, Math. Dept., Texas A&M University, April 1993.
9. G. Chen, Invited seminar, Math. Institute, The Technical Univ. of Denmark, Lyngby, Denmark, August 1993.
10. G. Chen, One hour talk, Minisymposium on Control of PDEs, Math. Dept., Texas A&M Univ., College Station, TX, October 1993.
11. G. Chen, J. Zhou and C.H. Chen, 20 minute talk in AMS Meeting #886, College Station, TX, October 1993.
12. G. Chen, One hour pretalk for Frontier Lecture Series, Math. Dept., Texas A&M University, October 1993.
13. G. Chen, Y. Deng, W.M. Ni and J. Zhou, 30 minute talk, Numerical Analysis and Optimization, International Federation for Information Processing, Rabat, Morocco, December 1993.

The PI's have organized/chaired the following:

1. G. Chen and J. Zhou, Invited Special Session in SIAM Conference on Control in the 90's, Minneapolis, September, 1992.
2. J.E. Lagnese and G. Chen, Invited Session in IEEE Control and Decision Conference, Tucson, December 1992.

3. G. Chen and J. Zhou, Minisymposium on Control of PDEs, Math. Dept. Texas A&M Univ., College Station, TX, October 1993.
4. G. Chen and J. Zhou, Special Session on Control Systems Governed by Partial Differential Equations, AMS Meeting #886, College Station, TX, October 1993.

G. Chen has also served as Associate Editor of SIAM J. Control & Optimization, January 1, 1992-present. He was also Invited Professor at the Mathematical Institute, The Technical University of Denmark, Copenhagen, 8/2-8/16, 1993 (with travel, living expenses and honorarium paid by the host).

IV. Personnel

Dr. G. Chen is the principal investigator in charge of the overall conduct of the grant. Dr. J. Zhou is the co-principal investigator. With regard to the research in this grant, Dr. Chen works primarily on the PDE theory, stabilization, engineering models and applications, while Dr. Zhou works on the aspects of optimization, scientific computation and computer graphics. This collaboration enables the P.I.s to cover many different types of distributed parameter control problems of contemporary interest.

Five Ph.D. students are currently working with the PI's: Messrs. C.H. Chen, Y. Deng, Z. Ding, C. Li and P. You. The first three have been receiving summer supports from this grant for two years. They are expected to graduate in 1994. Copies of their Ph.D. dissertations will be forwarded to the Program Manager once these students complete their Ph.D. study here.

V. Interaction with Air Force Laboratory

Dr. V. Venkayya, Principal Scientist at the Analysis and Optimization Branch, Structures Division of Wright Laboratory, Wright-Patterson AFB, Ohio, was invited by Dr. Chen to give a technical presentation at Texas A&M University on October 13, 1992. Dr. G. Chen paid a reciprocal visit and gave a technical seminar at Wright Laboratory in late February 1993. Many questions were discussed, with Dr. Venkayya's group during the visit.

Dr. G. Chen plans to visit Dr. Venkayya's group (and possibly other groups as well) at the AF Wright Laboratory in June 1994.

VI. Video production

In late January 1993, we made a video (by home camcorder) from our Hewlett Packard 9000 Series 710 Workstation for the visualization of *special phenomena (studied in our CRC Press book) of focusing, whispering gallery, bouncing ball and wave penetration* in vibration and wave propagation. We believe this is the first time such phenomena are visualized and animated. A video cassette was sent to Dr. Marc Q. Jacobs, Program Manager at AFOSR in January. This video was also presented at a technical seminar by Dr. G. Chen at Wright Air Force Laboratory in Dayton, Ohio in February 1993 with favorable response.

In September 1993, another short ($5\frac{1}{2}$ minutes) video entitled "Some Controlled Heat Phenomena" was also made. This video visualizes the boundary control of a linear-quadratic regulator problem governed by the heat equation in 2D. It was presented at the American Mathematical Society Meeting #886 held at College Station, Texas in October 1994.

VII. Technology Transitions

The publication of our two books "Boundary Element Methods" and "Vibration and Damping in Distributed Systems" (and other research articles) have begun to exert impacts in the research and applications of distributed parameter systems. We have received requests of boundary element software developed by us from mathematics and engineering researchers. We are hoping to further strengthen our ties with certain research groups at Wright AF Laboratory and propagate to them the mathematical techniques and numerical software developed by us here.

Dr. J. Zhou visited AAC (Automated Analysis Corp.) in Ann Arbor, Michigan, in late May 1993. AAC is one of the major commercial users of boundary element methods. Dr. Zhou discussed at length with the technical managers and scientists at AAC for possible transfers of our boundary element packages to AAC for commercial use. Further discussions with them are being continued.

We are also planning to make new video productions to publicize our capabilities so that R&D people in civilian technology may understand and adopt our mathematical products.