Modeling, Inverse Problems and Feedback Control for Distributed Dynamical Systems

FINAL TECHNICAL REPORT

for the period

January 15, 1998 - November 30, 2000

AFOSR F49620-98-1-0180

Program Manager:

Marc Q. Jacobs
AFOSR/NM
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

Principal Investigators:

Dr. H.T. Banks
email: htbanks@eos.ncsu.edu
FAX: 919-515-1636
Phone: 919-515-3968
Dr. R.C. Smith
email: rsmith@eos.ncsu.edu
FAX: 919-515-1636
Phone: 919-515-7552
Center for Research in Scientific Computation
Box 8205
North Carolina State University
Raleigh, NC 27695-8205

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

0214

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 26, 2001	3. REPORT TYPE AND DATES COVERED FINAL TECHNICAL REPORT January 15, 1998 – November 30, 2000

4. TITLE AND SUBTITLE

Final Report on AFOSR grant F49620-98-1-0180
"Modeling, Inverse Problems and Feedback Control in Distributed Dynamical Systems"

5. FUNDING NUMBERS

F49620-98-1-0180

6. AUTHOR(S)

Dr. H.T. Banks

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Center for Research in Scientific
Computation
Box 8205
North Carolina State University
Raleigh, NC 27695-8205

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NM
801 N. Randolph Street, Room 732
Arlington, VA 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

Progress is reported on modeling of toxic pathways for dioxin and trichloroethylene, reduced order modeling in nonlinear coupled fluid/acoustics problems, electromagnetic interrogation of dispersive media and modeling of nonlinear hysteresis in materials.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Objectives

We pursued investigations in several distinct but related areas of research. The first topic of our research involves development of models and computational packages for systems arising in nonlinear acoustics. Problems in nonlinear structural acoustics (with direct reference to AF and DoD interests) are investigated. Specifically, computational modeling of payload cavities and shear layer flow induced acoustic fields in shallow cavities such as weapon and instrument bays on military aircraft.

A second area of our research efforts entailed continuation of health sciences investigations in collaboration with scientists in the Mathematical Products Division, Air Force Research Labs, Brooks AFB. Specific topics being investigated include modeling of microwave pulses in dispersive media and their potential for use in medical imaging as well as military surveillance and detection as well as modeling of toxin distribution, metabolism and elimination in human tissues.

Status of Effort

Investigators supported under this grant have made significant progress in the following areas: (1) PBPK modeling of the toxins TCDD and TCE, (2) computational methods for control design in open cavity acoustics problems, (3) the modeling and estimation of dielectric parameters and geometry in materials using electromagnetic pulses and eddy current techniques, (4) modeling, estimation and control of smart material devices. In all cases, the basic physics or biology underlying the process is incorporated in the model and utilized to the extent possible in parameter estimation and/or control design.

Accomplishments

1. *Modeling of Toxins in Human Uptake, Metabolism and Elimination*

1a. *Hepatic Uptake and Elimination of 2,3,7,8 - Tetrachlorodibenzo-p-dioxin*

The objective of our research was the development of advanced pharmacokinetic modeling techniques to describe the transport of solutes within the liver. Our particular interest is the chemical compound 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). TCDD enters in the environment through combustion sources such as the burning of municipal and hospital wastes and in the production of certain herbicides. In particular, TCDD is an unwanted by-product in the manufacture of 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) which was a primary component of Agent Orange used by US forces during the Vietnam conflict. A number of studies have been conducted to determine possible adverse health effects in Vietnam-era veterans who may have been exposed to Agent Orange. Of paricular concern to researchers is TCDD's ability to produce a wide range of effects in animals following exposure, including certain types of cancer.

Physiologically-based pharmacokinetic models which have attempted to describe the hepatic uptake, distribution, and elimination of TCDD have generally used the well-stirred or venous-equilibrium model to describe events occurring in the liver. The basic assumption of this model, that the concentration of solute is uniform throughout the length of the liver acinus, does not describe the elimination of solutes with decreasing concentration gradients along the acinus following a bolus input. In addition, the "well-stirred" model cannot accommodate spatial variations in other parameters, such as enzyme activity and hepatic cell permeability.

We have developed a convection-dispersion model for the hepatic uptake and elimination of TCDD. This model incorporates the complex architecture and physiology of the human liver and includes the dynmaics of TCDD interaction with two intracellular proteins, the Ah receptor and cytochrome P450 1A2 [6]. The resultant mathematical model is a nonlinear coupled system of partial differential equaions and ordinary differential equations with time delay. We have established the well-posedness of the model [7], have developed approximation methodologies (with convergence arguments) for numerical simulation and the inverse problem, and are continuing initial promising simulation findings. A summary of theoretical and numerical results to date is given in the Ph.D. thesis of Musante [8] and subsequent computational results are found in [21].

1b. *Modeling of Trichloroethylene in Adipose Tissue*

In subsequent work [55] we studied three physiologically based pharmacokinetic (PBPK) models for the systemic transport of trichloroethylene (TCE), with a focus on the adipose, or fat tissue. TCE is a widespread environmental contaminant, and has been shown to produce toxic effects in both animals and humans. A key characteristic of TCE is its tendency to acculmulate in fat tissue, which has a major impact on the overall systemic disposition of TCE.

We used PBPK models to predict the kinetics of TCE through the various tissues and organs, including the adipose tissue. The first model utilizes the standard "perfusion-limited" compartmental model for the fat tissue, while the second model uses a "diffusion-limited" model to describe the transport through the adipose tissue. Both of these ODE models are based on "well-mixed" and rapid equilibrium assumptions, and do not take into account the specific and largely heterogeneous physiology of adipose tissue.

The third model we investigate is a PBPK hybrid model with an axial-dispersion type model for the adipose tissue similar to that used in the hepatic TCDD models described above. This PDE-based model is designed to capture key physiological heterogeneities of fat tissue, including widely varying fat cell sizes, lipid distribution, and blood flow properties. Model simulations demonstrate that this model may be well-suited to predict the experimental behavior of TCE in adipose tissue using parameter estimation techniques.

2. *Reduced Order Modeling in Control of Open Cavity Acoustics*

Aircraft with internal carriage of weapons or surveillance systems require active control strategies to limit high amplitude open bay acoustic resonances and to facilitate optimization of structure requirements and weapon/surveillance reliability. We have carried out investigations of the use of numerical simulation combined with Proper Orthogonal Decomposition (POD) model reduction methods to optimize an active control system for aircraft open cavity applications. Issues addressed include characterizing shear layer and wake resonant responses, optimal steady blowing rates, the effect of open loop harmonic perturbations, use of POD for post-processing data to reduce storage requirements, and the use of the Nelder-Mead optimization procedure. Comparison of the wake and shear layer responses reveals why a wake response in aircraft is undesirable. This study has focused primarily on a freestream flow at M=0.85 with a cavity of aspect ratio l/d=4.5. The results include the use of steady blowing injection up to M = 0.9 and harmonic forcing perturbations ranging in amplitude from M=0.005 to M=0.45. In the parameter space examined, fluid displacement had the largest effect. The best observed forcing reduced the buffet loading metrics by approximately 17 db. These findings are reported in [44, 48].

3. *Electromagnetic Interrogation of Dielectric Materials*

Significant progress has been achieved in two areas of focus in our continuing efforts on use of electromagnetic signals to interrogate materials. In collaborative efforts with the group led by Dr. R.A. Albanese, AFRL, Brooks AFB, we have developed computational methods for the inverse problems of using both conductive interfaces and acoustic wavefronts as reflectors to promote microwave pulse interrogation of materials for both dielectric properties and geometry. The details of the initial work appeared in a monograph [46] published by SIAM and in [36]. Continuing efforts involve tracking traveling acoustic waves through heterogeneous media via electromagnetic pulse reflections as well as model development for polarization in nonlinear materials.

A second focus of our efforts involves the use of ECT (eddy current techniques) to detect subsurface damage (cracks, disbonds, etc.) in structures. Eddy currents are produced in the structure under interrogation and observations of the associated magnetic fields with GMR (Giant Magneto Resistive) sensors can be used to detect structural anomalies. We have successfully developed reduced order computational methods (reported in [33, 34, 35]) based on Karhunen - Loéve reduced basis techniques for the associated inverse problems. This is a joint effort with a NASA team of scientists led by Dr. W. Winfree (NASA Langley Research Center) but it has great relevance to AF and DoD needs in the area of damage detection in aircraft and other military structures. We have demonstrated the ability to determine both geometry and depth of subsurface occlusions. These techniques have recently been successfully validated in experimental efforts at NASA Langley.

4. *Model Development and Control Design for Smart Materials with Hysteresis*

We have significant progress on modeling and design of smart material devices with focus in several distinct but related areas.

In collaborations with scientific teams at Lord Corporation, we have made major advances in two types of smart material vibration suppression type devices. Significant progress has been made in understanding the constitutive relationship between applied magnetic field and rheological response in magnetorheological (MR) fluids. Computational methods (resulting in software packages now being used at Lord in material design) based on both homogenization and fast multi-pole methods (for complete near field particle force interactions) have been successfully developed and experimentally validated [20, 24, 32, 43]. A second project with Lord scientists deals with the understanding of nonlinear hysteresis in elastomers (filled viscoelastic rubber-like materials structures used in damping devices). Our contributions [31, 37, 51, 52] have involved leading edge technology and the models have been experimentally validated for structural samples in both shear and extension. Recent extensions and transitions have resulted in a Rubber Division, American Chemical Society best paper award for the paper [53]. The computational ideas developed in this context have proved useful in our investigation on characterization of shear waves in viscoelastic materials [50] as well as modeling of polarization in nonlinear materials.

A second area of investigation has focused on the development of models, commensurate numerical and parameter estimation methods, and model-based control techniques for high performance smart material transducers which exhibit hysteresis and constitutive nonlinearities. The initial emphasis centered on the ferromagnetic material Terfenol-D and the ferroelectric compounds PZT and PMN due to their prevalence in broadband applications. The scope of the investigation has recently been expanded to include certain ferroelastic compounds, including the shape memory alloy Nitinol, due to their capability for generating large strains. The commonality between these compounds is provided by the domain structure inherent to the materials, and one goal of the investigation is to utilize this ferroic structure to develop unified low-order models which facilitate subsequent control design. The consideration of model development and control design as symbiotic processes provides the possibility for significantly expanding the capability of high performance smart material transducers in aeronautic, aerospace, defense, and industrial applications.

Models and control algorithms were first developed for magnetostrictive transducers employed in applications which require large input forces (e.g., sonar transducers, high speed milling lathes). The initial models focused on the quantification of the direct and converse magnetoelastic effects [10, 57, 60, 61, 62, 63] while later components of the investigation have centered on the incorporation of frequency and design properties of the transducers [64, 66]. Both theoretical and implementational issues concerning the design of control algorithms which utilize the models have also been investigated in the context of magnetostrictive transducers [68, 69, 77, 78]. As reported in [69], the use of inverse compensators constructed from the nonlinear hysteresis models have yielded accuracies of ± 2 microns at a rotation rate of 3000 rpm for a milling machine employing a magnetostrictive transducer.

A second facet of the investigation has focused on the development of analogous models for ferroelectric materials including the electrostrictive compound PMN and piezoceramic actuators/sensors (PZT). The initial theory for ferroelectric materials was presented in [65, 70, 71] and extensions to incorporate the temperature-dependence in relaxor ferroelectric materials is summarized in [72]. The extension of the models to piezoceramic transducers was reported in [73, 74, 75, 76]. Finally, results from an initial investigation incorporating the model-based compensators into amplifier design are reported in [58, 59]. The extension of the control techniques described in [69, 77, 78] to piezoceramic and electrostrictive actuators is under current investigation.

A summary of the common issues being addressed in the development of models, numerical algorithms and control techniques for high performance transducers which utilize these materials is provided in the chapter [67]. This reference also indicates some of the issues associated with the extension of these techniques to shape memory alloys which is also under current investigation.

Personnel Supported

H.T. Banks, R.C. Smith, A.B. Cain, D. Rubio, G.A. Pinter, R.C.H. del Rosario, D.M. Bortz, L.K. Potter, J.K. Raye, S.C. Beeler and B. Browning.

Interactions

H.T. Banks - Presentations

1. ARO Damping Workshop, VPISU, Blacksburg, VA, October 19-22, 1998.
2. Intl. Conf. on Semigroups of Operators: Theory and Applications, Newport Beach, Ca, December 14-18, 1998.
3. Institute for Mathematical Systems, Universitat Groningen, The Netherlands, January 6-9, 1999.
4. SPIE Symposium on Smart Structures and Materials, Newport Beach, CA, March 1-4, 1999.
5. AMS Western Regional Conference, Las Vegas, NV, May 9-11, 1999.
6. AIAA/CEAS Aeroacoustics Conference, Bellvue, WA, May 10-12, 1999.
7. NSF Workshop on Active Flow Control, University of California, San Diego, May 31-June 1, 1999.
8. SIAM Math-In-Industry Workshop, Harvey Mudd College, Claremont, CA, June 16-19, 1999.
9. Workshop on Control, System Theory and Mathematical Modeling, Gadjah Mada University, Yogyakarta, Indonesia, July 19-23, 1999.

10. International Conference on Math and Its Application, SE Asian Math Society, Gadjah Mada University, Yogyakarta, Indonesia, July 26-29, 1999.
11. Intl. Workshop on Systems with Hysteresis, Weierstrass Institute for Applied Analysis and Stochastics, Berlin, September 20-24, 1999.
12. SIAM Conf. in Industrial Applied Mathematics, Raleigh, NC, Oct. 10-12, 1999.
13. Conf. on Advances in Control of Nonlinear Distributed Parameter Systems, Texas A&M University, College Station, TX, Oct. 22-23, 1999.
14. Invited Survey Lecture, SPIE Symposium on Smart Materials and Structures, Newport Beach, CA, March 5-9, 2000.
15. Trends in Dynamical Systems, Institute of Mathematics, Universität Graz, Graz, Austria, March 16-18, 2000.
16. Plenary Lecture, SIAM-SEAS Annual Conference, Univ.-Georgia, Athens, GA, March 24-25, 2000.
17. AMS Symposium on Mathematical Models in the Biological and Physical Sciences, Univ. Louisiana-Lafayette, April 14-16, 2000.
18. Workshop on Principal Orthogonal Decomposition and its Applications, Graz, Austria, May 25-27, 2000.
19. Conference on Optimal Control of Complex Dynamical Structure, Mathematiches Forschungsinstitut Oberwolfach, Germany, June 4-10, 2000.
20. Plenary Lecture, 2nd European Conference on Structural Control, Ecole Nationale des Points et Chaussess, Champs-sur-Marne, France, July 3-6, 2000.
21. Conference on Computation and Control VII, Bozeman, MT, August 1-4, 2000.
22. International Workshop on Hysteresis, Univ. Ill.-Chicago, August 28-30, 2000.

R.C. Smith - Presentations

1. SPIE's Sixth Annual Symposium on Smart Structures and Materials, Newport Beach, CA, March 1-4, 1999.
2. Eighteenth Annual Conference on Properties and Applications of Magnetic Materials, Illinois Institute of Technology, Chicago, IL, April 28, 1999.
3. 1999 U.S. Navy Workshop on Acoustic Transduction Materials and Devices, Penn State University, State College, PA, April 14, 1999.
4. Colloquium, Department of Mathematics, Virginia Polytechnic Institute and State University, Blacksburg, VA, October 23, 1998.
5. Colloquium, Department of Applied Mechanics and Engineering Sciences, University of California, San Diego, CA, March 5, 1999.
6. Colloquium, Department of Electrical Engineering and Institute for Systems Research, University of Maryland, College Park, MD, March 15, 1999.
7. "Modeling and Control Issues Concerning Smart Materials with Hysteresis," NSF-CBMS Workshop on Control of Distributed Parameter Systems, University of Nebraska, Lincoln NE, August 10, 1999.
8. "Modeling and Control Issues Concerning Smart Materials with Hysteresis," Fourth ARO Workshop on Smart Structures, Penn State University, State College, PA, August 16, 1999.
9. "Modeling and Control Issues Concerning Smart Materials with Hysteresis," Colloquium, Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, September 20, 1999.
10. "Modeling and Control Issues Concerning Smart Materials," Session on Engineering Acoustics: Transducer Loss Mechanisms, 138th Meeting of the Acoustical Society of America, Columbus, OH, November 1, 1999.
11. "Modeling and Control Issues Concerning Smart Materials with Hysteresis," Adaptive Structures and Material Systems Symposium, 1999 ASME International Mechanical Engineering Congress and Exposition, Nashville, TN, November 17, 1999.
12. "Modeling Aspects Concerning THUNDER Actuators," Adaptive Structures and Material Systems Symposium, 1999 ASME International Mechanical Engineering Congress and Exposition, Nashville, TN, November 18, 1999.

13. "Modeling and Optimization Issues Concerning a Circular Piezoelectric Actuator Design," Adaptive Structures and Material Systems Symposium, 1999 ASME International Mechanical Engineering Congress and Exposition, Nashville, TN, November 18, 1999.
14. "Modeling and Control Issues Concerning Smart Materials with Hysteresis," Smart Materials Symposium, Fall Meeting of the Materials Research Society, Boston, MA, December 2, 1999.
15. "Inverse Compensation for Hysteresis in Piezoceramic, Electrostrictive and Magnetostrictive Materials," Session on Control of Distributed Parameter Systems: New Approaches and Applications, 38th IEEE Conference on Decision and Control, Phoenix, AZ, December 9, 1999.
16. "A Domain Wall Model for Hysteresis in Piezoelectric Materials," SPIE's Seventh Annual Symposium on Smart Structures and Materials, Newport Beach, CA, March 7, 2000.
17. "Control Strategies for Smart Material Systems with Hysteresis," SPIE's Seventh Annual Symposium on Smart Structures and Materials, Newport Beach, CA, March 7, 2000.
18. "A Temperature-Dependent Constitutive Model for Relaxor Ferroelectrics," SPIE's Seventh Annual Symposium on Smart Structures and Materials, Newport Beach, CA, March 8, 2000.
19. "A Magnetoelastic Model for Magnetostrictive Sensors," 2000 U.S. Navy Workshop on Acoustic Transduction Materials and Devices, Penn State University, State College, PA, April 12, 2000.
20. "A Domain Wall Model for Hysteresis in Piezoelectric Materials," 2000 U.S. Navy Workshop on Acoustic Transduction Materials and Devices, Penn State University, State College, PA, April 13, 2000.
21. "Modeling and Control Issues Concerning Smart Materials with Hysteresis," Colloquium, Department of Electrical Engineering, Iowa State University, Ames, IA, May 12, 2000.
22. "Development and Validation of a Hysteresis Model for Piezoelectric Actuators," Session on Analytic and Experimental Characterization of Piezoelectric Materials, Third SIAM Conference on Mathematical Aspects of Materials Science, Philadelphia, PA, May 23, 2000.
23. "Partial and Full Inverse Compensation for Hysteresis in Smart Material Systems," Session on Control of Distributed Parameter Systems, 2000 American Control Conference, Chicago, IL, June 29, 2000.

D.M. Bortz

1. AIAA Conference, Maui, June 12-14, 2000.

Transitions

1. PBPK Modeling: Development of models and associated software in conjunction with R. Albanese's group at AFRL (see below) and M. Evans, EPA (tel. 919-541-0838). These models have great relevance to AF and DoD due to the presence of TCDD and TCE at many military bases.
2. Nonlinear Acoustics: Development of models and associated software for simulations and control in shallow cavity acoustics involves collaboration and interaction with Mick Stanck, AFRL, Wright Patterson AFB.
3. Electromagnetic Interrogation of Dispersive Media: Problem formulation and method development involves close collaboration with Dr. Richard Albanese (tel: (210) 536-5710) and colleagues at AFRL, Brooks AFB. The reflection acoustic grating problems mentioned above have direct application to Albanese-led efforts on material detection and interrogation of interest to AF and DoD (location of subsurface mines, bunkers, characterization of weapons systems stealth technology). The project using eddy current techniques in subsurface damage detection is in collaboration with Dr. William Winfree (tel:(717)864-4963) and colleagues at NASA Langley Research Center, Hampton, VA. The methods developed to date are being used in experimental efforts at NASA Langley in our efforts with this group.
4. Modeling of Smart Material Damping Devices: Our efforts on inverse problem methodology have been directly transitioned to problems on design of "smart" fluids and elastomers at Lord Corporation, Cary, NC. Collaborative efforts with scientists (contact: Mark Jolly (tel:(919) 469-2500, ext. 2335)) have benefited enormously from use of computational ideas and methods developed under AFOSR support through this grant and its predecessors. The efforts on magnetostrictive transducers including models, numerical methods and control techniques has been transitioned to Etrema Products, Ames, IA, where our software is being used in design. Contact points are R. Zrostlik (tel:(515) 296-7953) and J. Slaughter (tel: (515) 296-6826).

Honors/Awards

- Banks, IEEE Fellow, 1994.
- Banks, IEEE CSS Systems Technology Award, 1996.
- Banks, Distinguished Alumnus Award, Purdue University, 1998.
- Banks, Elected Chairman, SIAM Board of Trustees, 1999; re-elected, 2000.
- Banks, Institute of Physics Fellow, 1999.
- Banks, Alumni Distinguished Graduate Professor, NCSU, 2000.
- Banks (with Yeoh and Pinter), Best Paper Award, 158^{th} Meeting Rubber Division, American Chemical Society, Cincinnati, OH, October, 2000.
- Smith, Early Achievement Award, Iowa State University, 1997.
- Banks and Smith (with Silcox), 1995 ASME Adaptive Structures "Best Paper Award in Structural Dynamics and Control", Adaptive Structures Forum, Salt Lake City, Utah, April, 1996.

Publications

Publications of work partially supported under this grant during the reporting period are listed below as references.

References

[1] H.T. Banks, M.W Buksas, and Y. Wang, "A time domain formulation for identification in electromagnetic dispersion," CRSC TR96-30; *J. Math. Systems, Estimation and Control*, 8, pp. 257-260, 1998.

[2] H.T. Banks and M.W. Buksas, "Electromagnetic interrogation of dielectric materials," CRSC-TR98-30; August, 1998.

[3] H.T. Banks, R.C.H. del Rosario and R.C. Smith, "Reduced order model feedback control design: Numerical implementation in a thin shell model,"CRSC-TR98-27, July, 1998; *IEEE Trans AC*, **45** (2000), pp. 1312-1324.

[4] H.T. Banks and P. Emeric , "Detection of non-symmetrical damage in smart plate-like structures," CRSC-TR98-5; *J. Intell. Material Systems and Structures*, **10** (1998), pp.818-828.

[5] H.T. Banks and Tao Lin, "Determining the structure of a biological medium using acousto-optic probes," CRSC-TR98-21, May, 1998; *J. Inverse and Ill-Posed Problems*, **7**(1999), pp. 61-82.

[6] H.T. Banks, C.J. Musante and H.T. Tran, "A dispersion model for the hepatic uptake and elimination of 2,3,7,8-tetrachorodibenzo-p-dioxin (TCDD)," CRSC-TR97-29; *Math. and Comput. Modeling*, **28**, 1998, pp. 9-29.

[7] H.T. Banks and C.J. Musante, "Well-posedness for a class of abstract nonlinear parabolic systems with time delay," CRSC-TR97-30; *Nonlinear Analysis: Theory, Methods and Applications*, **35** (1998), pp. 629-648.

[8] C.J. Musante, "A Distributed Parameter Model for Spatially Dependent Hepatic Processing of 2,3,7,8-TCDD,"Ph.D. Thesis, North Carolina State University, May, 1998.

[9] H.T. Banks and R.H. Fabiano, "Approximation issues for applications in optimal control and parameter estimation", CRSC-TR97-11, April, 1997; *Modeling and Computation for Applications in Mathematics, Science and Engineering* (J.W. Jerome, ed.), Oxford University Press, June, 1998, pp. 141-165.

[10] H.T. Banks and R.C. Smith, "Hysteresis modeling in smart material systems", in *Smart Materials and Structures*, (G.R. Tomlinson and W.A. Bullough, eds), IOP Publishing, July, 1998; pp. 675-682; *Applied Mechanics and Eng.* **5** (2000), pp. 31-45.

[11] H.T. Banks, G.A. Pinter, L.K. Potter, B.C. Muñoz, and L.C. Yanyo, "Estimation and control related issues in smart material structures and fluids", CRSC-TR98-2, January, 1998; *Optimization Techniques and Applications* (L. Caccetta, et al., eds.), Curtain Univ. Press, July 1998, pp. 19-34.

[12] H.T. Banks, S.R. Durso, M.A. Goodhart, and M.L. Joyner, "On the radio-frequency inputs in dipolar heating of adhesives", CRSC-TR98-3, January, 1998; *J. Microwave Power and Electromagnetic Energy*, **33** (1998), pp. 231-242.

[13] H.T. Banks, N.G. Medhin and Y. Zhang, "Mathematical model and analysis of a laminated beam with shear", CRSC-TR98-4, January, 1998; *Dynamic Systems and Applications*, **7**(1998), pp. 291-318.

[14] H.T. Banks and F. Kojima, "Boundary shape identification in two dimensional electrostatic problems using SQUIDs", *J. Inverse and Ill-Posed Problems*, **8** (2000), 487-504.

[15] H.T. Banks and G.A. Pinter, "Approximation results for parameter estimation in a class of abstract nonlinear hyperbolic systems", *Applied Mathematics Letters*, **12** (1999), pp. 129-133.

[16] H.T. Banks, "Remarks on well-posedness theorems for damped second order systems", CRSC-TR98-16, April, 1998; *Applied Mathematics Letters*, **12** (1999), pp. 21-24.

[17] H.T. Banks and I. Groselj, "A comparison of noise generation techniques and the effects on inverse problem calculations", CRSC-TR98-17, April, 1998; Matimyá Matematika, Math Society of the Philippines, August (1998), pp. 1-17.

[18] H.T. Banks, S. Durso, M. Goodhart, and K. Ito, "Nonlinear exothermic contributions to radio-frequency bonding of adhesives", CRSC-TR98-27, June 1998; *Nonlinear Analysis: Theory, Method and Application, Series B*, to appear.

[19] H.T. Banks and J. Zhou, "Regularity and approximation of systems arising in electromagnetic interrogation of dielectric materials", CRSC-TR98-33, September, 1998; *Num. Func. Analy. Opt.* **20** (1999), pp. 609-627.

[20] H.T. Banks, T.M. Simon, F. Reitich, M.R. Jolly and K. Ito, "Estimation of the effective permeability in magnetorheological fluids", CRSC-TR98-35, October, 1998; *J. Intl. Material Systems and Structures* **10** (1999), pp. 872-879.

[21] H.T. Banks, C.J. Musante and J.K. Raye, "Predictions for a distributed parameter model describing hepatic processing of 2,3,7,8 -Tetrachlorodibenzo-p-dioxin", CRSC-TR98-38, November, 1998; *Math. and Comput. Modeling* **33** (2001), pp. 49-64.

[22] H.T. Banks, "Remarks on uncertainty assessment and management in modeling and computation", CRSC-TR98-39, November, 1998; *Math. and Comput. Modeling,* **33** (2001), pp. 39-47.

[23] H.T. Banks and R.C.H. del Rosario, "Convergence of approximations in feedback control of structures", CRSC-TR98-40, November, 1998; *Math. and Comput. Modeling* **33** (2001), pp. 65-78.

[24] H.T. Banks, T.M. Simon, F. Reitich, M.R. Jolly and K. Ito, "On the effective magnetic properties of magnetorheological fluids", CRSC-TR98-42, November, 1998; *Math. and Comput. Modeling* **33** (2001), pp. 273-284.

[25] H.T. Banks, G.A. Pinter and L.K. Potter, "Existence of a unique weak solution to a dynamical system for nonlinear elastomers with hysteresis", CRSC-TR98-43, November, 1998; *Differential and Integral Equations,* **13** (2000), pp. 1001-1024.

[26] H.T. Banks, G.A. Pinter, L.K. Potter, M.J. Gaitens, and L.C. Yanyo, " Modeling of quasi-static and dynamic load responses of filled viscoelastic materials", CRSC-TR98-48, December, 1998; *Modeling: Case Studies from Industry* (E. Cumberbatch and A. Fitt, eds.) Cambridge University Press, to appear.

[27] H.T. Banks and L.L. Zia, " Pointwise convergence of approximation schemes for parameter estimation in parabolic equations", *Applied Math Letters,* **12** (1999), pp. 27-30.

[28] H.T. Banks, H.V. Ly, F. Reitich, M.R. Jolly and K. Ito, "Simulations of particle dynamics in magnetorheological fluids", CRSC-TR99-08, February, 1999; *J. Comp. Physics,* **155** (1999), pp. 60-177.

[29] H.T. Banks, D. Rubio and R.C. Smith, "Modeling of acoustic fields generated by flow past an open cavity", CRSC-TR99-13, February, 1999; in Proc. 5th AIAA/CEAS Aeroacoustics Conference (Bellevue, WA), May 10-12, 1999, pp. 267-277.

[30] H.T. Banks, G.M. Kepler and H.T. Tran, "Reduced order model compensator control of species transport in a CVD reactor", CRSC-TR99-15, April, 1999; *Optimal Control: Applications and Methods,* **21** (2000), pp. 143-160.

[31] H.T. Banks, G.A. Pinter, L.K. Potter, M.J. Gaitens and L.C. Yanyo, "Modeling of nonlinear hysteresis in elastomers under uniaxial tension", CRSC-TR99-09, February, 1999; *J. Intelligent Material Systems and Structures,* **10** (1999), pp. 116-134.

[32] H.T. Banks, H.V. Ly, K. Ito, M.R. Jolly, and F. Reitich, "Dynamic simulation of the temporal response of microstructure formation in magnetorheological fluids", CRSC-TR99-29, August, 1999; *Proc. 7th Intl. Conf. on ER, MR Suspensions and Applications,* (Honolulu, HI, July 19-23, 1999), (R. Tao, ed.), World Scientific, Singapore, 2000, pp.374-383.

[33] H.T. Banks, M.L. Joyner, B. Wincheski, and W.P. Winfree, "Evaluation of material integrity using reduced order computational methodology", CRSC-TR99-30, August, 1999.

[34] H.T. Banks, M.L. Joyner, B. Wincheski and W.P. Winfree, " Nondestructive evaluation using a reduced-order computational methodology", ICASE Tech. Rep. 2000-10, NASA Langely Res. Ctr., March 2000; *Inverse Problems* **16** (2000), pp. 929-945.

[35] H.T. Banks, M.L. Joyner, B. Wincheski and W. Winfree, "A reduced order computational methodology for damage detection in structures", *Nondestructive Evaluation of Ageing Aircraft, Airports and Aerospace Hardware* (A.K. Mal, ed.) SPIE **3994** (2000), pp. 10-17.

[36] H.T. Banks and M.W. Buksas, "A semigroup formulation for electromagnetic waves in dispersive dielectric media", CRSC-TR99-34, November, 1999; *Nonlinear PDE & Their Applications, College de France Seminar Series,* to appear.

[37] H.T. Banks and G.A. Pinter, "Damping: hysteretic damping and models", CRSC-TR99-36, December, 1999; *Encyclopedia of Vibrations,* Academic Press, London, to appear.

[38] H.T. Banks, C.J. Musante and J.K. Raye, "Approximation methods for inverse problems governed by nonlinear parabolic systems", CRSC-TR99-38, December, 1999; *Num. Func. Anal. & Optim.,* **21** (2000), pp. 791-816.

[39] H.T. Banks and K.L. Bihari, "Modeling and estimating uncertainty in parameter estimation", CRSC-TR99-40, December, 1999; *Inverse Problems,* **17** (2001), pp. 1-17.

[40] H.T. Banks, G.M. Kepler and H.T. Tran, "Compensator control for chemical vapor deposition film growth using reduced order design models", CRSC-TR99-41, December, 1999; *IEE Trans. Semiconductor Manuf.*, to appear.

[41] H.T. Banks, R.C.H. del Rosario and H.T. Tran, "Proper orthogonal decomposition based control of transverse beam vibrations: experimental implementation", CRSC-TR99-43, December, 1999; *IEEE Trans. Control Systems Tech.*, submitted.

[42] H.T. Banks, S.C. Beeler and H.T. Tran, "Feedback control methodologies for nonlinear systems", CRSC-TR99-44, December, 1999; *J. Opt. Theory Applic.*, **107** (2000), pp. 1-33.

[43] H.T. Banks, C.H. Lee, F. Reitich, M.R. Jolly and K. Ito, "A piecewise linear model for field-responsive fluids", CRSC-TR00-08; March, 2000; *IEEE Trans. on Magnetics*, to appear.

[44] A.B. Cain, A.D. Rubio, D.M. Bortz, H.T. Banks and R.C. Smith, "Optimizing control of open bay acoustics", CRSC-TR00-09; May, 2000; Proc. AIAA, AIAA-2000-1928, Maui, June 2000.

[45] H.T. Banks, A.S. Ackleh and K. Deng, "A finite difference approximation for a coupled system of nonlinear size-structured populations", CRSC-TR00-11; May, 2000; *Nonlinear Analysis*, submitted.

[46] H.T. Banks, A.S. Ackleh and G.A. Pinter, "On a nonlinear beam equation", CRSC-TR00-14; May, 2000; *App. Math. Letters*, submitted.

[47] H.T. Banks, N. Dietz and K. Ito, "Real-time process monitoring by p-polarized reflectance spectroscopy and closed-loop control of vapor phase epitaxy", CRSC-TR00-15; May, 2000; The Encyclopedia of Materials Science and Technology, (K. Bachmann, ed.) Elsevier Sci. Ltd., 2000, to appear.

[48] D.M. Bortz, A.D. Rubio, H.T. Banks, A.B. Cain and R.C. Smith, "Reduced order modeling in control of open cavity acoustics", CRSC-TR00-18; July, 2000; *Intl. J. Aeroacoustics*, submitted.

[49] H.T. Banks, M.W. Buksas and T. Lin, *Electromagnetic Material Interrogation Using Conductive Interfaces and Acoustic Wavefronts*, Frontiers in Applied Mathematics **21**, SIAM Publ., August, 2000.

[50] H.T. Banks, A. Eberhardt, J. Hayes, H.T. Tran and S. Wynne, "Modeling and computation of propagating waves from coronary stenoses", CRSC-TR00-20; August, 2000, *Comp. and Applied Math.* submitted.

[51] A. Ackleh, H.T. Banks and G.A. Pinter, " Well-posednes results for models of elastomers", CRSC-TR00-21; September, 2000, *J. Math. Anal. Appl.*, submitted.

[52] H.T. Banks and N.G. Medhin, "A molecular based dynamic model for viscoelastic responses of rubber in tensile deformations", CRSC-TR00-27, October, 2000; *Nonlinear Studies*, submitted.

[53] H.T. Banks, O.H. Yeoh and G.A. Pinter, "Compression of bonded rubber blocks", Proc. Rubber Division, American Chemical Society, Cincinnati, OH, Oct. 17-20, 2000, Paper # 84; *Rubber Chemistry and Tech.*, submitted.

[54] H.T. Banks S.C. Beeler, G.M. Kepler and H.T. Tran, "Reduced order modeling and control of thin film growth in an HPCVD reactor", CRSC-TR00-33; December, 2000, SIAM *J. Appl. Math.*, submitted.

[55] R.A. Albanese, H.T. Banks, M.V. Evans and L.K. Potter, " Physiologically based pharmacokinetic models for the transport of trichloroethylene in adipose tissue", CRSC-TR01-03; January, 2001 *Bull. Math. Biology* submitted.

[56] H.T. Banks and R.C. Smith, "Hysteresis Modeling in Smart Material Systems," *Applied Mechanics and Engineering*, 5(1), pp. 31-45, 2000.

[57] F.T. Calkins, R.C. Smith and A.B. Flatau, "An Energy-Based Hysteresis Model for Magnetostrictive Transducers," *IEEE Transactions on Magnetics*, 36(2), pp. 429-439, 2000.

[58] S. Chandrasekaran, D.K. Lindner and R.C. Smith, "Optimization of Switching Amplifiers for Piezoelectric Actuators," Proceedings of the SPIE, Smart Structures and Materials, Newport Beach, CA, 2000.

[59] S. Chandrasekaran, D.K. Lindner and R.C. Smith, "Optimized Design of Switching Amplifiers for Piezoelectric Actuators," *Journal of Intelligent Material Systems and Structures*, to appear.

[60] M.J. Dapino, F.T. Calkins, R.C. Smith and A.B. Flatau, "A Magnetoelastic Model for Magnetostrictive Sensors," Active 99, Fort Lauderdale, FL, December 2-4, pp. 1193-1204, 1999.

[61] M.J. Dapino, R.C. Smith, L.E. Faidley and A.B. Flatau, "A Coupled Structural-Magnetic Strain and Stress Model for Magnetostrictive Transducers," *Journal of Intelligent Material Systems and Structures*, **11**(2), 2000, pp. 134-152.

[62] M.J. Dapino, R.C. Smith and A.B. Flatau, "A Coupled Structural-Magnetic Strain Model for Magnetostrictive Transducers," Proceedings of the SPIE, Newport Beach, CA, 1999, Volume 3668, pp. 405-416, 1999.

[63] M.J. Dapino, R.C. Smith and A.B. Flatau, "A Structural-Magnetic Strain Model for Magnetostrictive Transducers," *IEEE Transactions on Magnetics*, 36(3), pp. 545-556, 2000.

[64] M.J. Dapino, R.C. Smith and A.B. Flatau, "A Model for the ΔE Effect in Magnetostrictive Transducers," Proceedings of the SPIE, Smart Structures and Materials, Newport Beach, CA, 2000.

[65] J.C. Piquette and R.C. Smith, "Analysis and Comparison of Four Anhysteretic Polarization Models for Lead Magnesium Niobate (PMN)" *Journal of the Acoustical Society*, **108**(4), 2000, pp. 1651-1662.

[66] J.C. Slaughter, M.J. Dapino, R.C. Smith and A.B. Flatau, "Modeling of a Terfenol-D Ultrasonic Transducer," Proceedings of the SPIE, Smart Structures and Materials, Newport Beach, CA, 2000.

[67] R.C. Smith, "Smart Structures: Model Development and Control Applications," *Series on Applied and Computational Control, Signals, and Circuits (ACCSC)*, Editor: Biswa Datta, Birkhauser, to appear.

[68] R.C. Smith, "Inverse Compensation for Hysteresis in Magnetostrictive Transducers," *Mathematical and Computer Modeling*, **33** (2001), pp. 285-298.

[69] R.C. Smith, C. Bouton and R. Zrostlik, "Partial and Full Inverse Compensation for Hysteresis in Smart Material Systems," CRSC Technical Report CRSC-TR00-06; Proceedings of the 2000 American Control Conference, 2000.

[70] R.C. Smith and C.L. Hom, "A Domain Wall Model for Ferroelectric Hysteresis," Proceedings of the SPIE, Newport Beach, CA, 1999, Volume 3667, pp. 150-161, 1999.

[71] R.C. Smith and C.L. Hom, "A Domain Wall Theory for Ferroelectric Hysteresis," *Journal of Intelligent Material Systems and Structures*, 10(3), pp. 195-213, 1999.

[72] R.C. Smith and C.L. Hom, "A Temperature-Dependent Hysteresis Model for Relaxor Ferroelectrics," Proceedings of the SPIE, Smart Structures and Materials 2000, Newport Beach, CA, Volume 3992, pp. 267-278, 2000.

[73] R.C. Smith and Z. Ounaies, "A Hysteresis Model for Piezoceramic Materials," Proceedings of the Winter Annual Meeting of the ASME.

[74] R.C. Smith and Z. Ounaies, "A Model for Asymmetric Hysteresis in Piezoceramic Materials," in *Materials for Smart Systems III*, Materials Research Society Symposium Proceedings Volume 604, 2000, pp. 285-290.

[75] R.C. Smith and Z. Ounaies, "A Domain Wall Model for Hysteresis in Piezoelectric Materials," *Journal of Intelligent Material Systems and Structures*, **11**(1), 2000, pp. 62-79.

[76] R.C. Smith, Z. Ounaies and R. Wieman, "A Model for Rate-Dependent Hysteresis in Piezoceramic Materials Operating at Low Frequencies," Proceedings of the SPIE, Smart Structures and Materials 2000, Newport Beach, CA, Volume 3992, pp. 128-136, 2000.

[77] R.C. Smith and R. Zrostlik, "Inverse Compensation for Ferromagnetic Hysteresis," CRSC Technical Report CRSC-TR99-28; Proc. 38th IEEE Conf. Dec. and Control, Phoenix, AZ, 1999.

[78] R.L. Zrostlik, A.B. Flatau and R.C. Smith, "Active Vibration Control of a Compliant Structure Using a Magnetostrictive Actuator," Proceedings of the SPIE, Newport Beach, CA, 1999.