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Research efforts and achievements in the area of modeling and control in distributed parameter physical systems are summarized. Progress is reported on specific topics including (i) control of structure borne noise/mechanical vibrations, (ii) modeling of hepatic uptake and elimination of dioxin, (iii) modeling and parameter estimation in electromagnetic field/solid interactions, and (iv) vibration based damage detection and health monitoring.

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Modeling and Control in Distributed Parameter Physical Systems

FINAL TECHNICAL REPORT

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Executive Summary

We have carried out research in the modeling and control of specific physical and biological distributed parameter (partial differential equation) systems. Our efforts involved theoretical, computational, and experimental aspects of the problems addressed. As part of our modeling efforts, specific inverse or parameter estimation problems were investigated.

A major thrust of our work involved research on health sciences related issues of interest to the Air Force and is collaborative with scientists in the Armstrong Lab, Brooks AFB. Specific topics investigated include control of electromagnetic signals in dispersive media, advanced pharmocodynamic modeling as a component of a computational therapeutic modeling methodology, and inverse problems related to vibration based damage detection and health monitoring.

A second major thrust entailed continuing efforts in modeling and control of fluid/structure interactions, specifically structural acoustics systems. This effort, on the use of structurally mounted piezoceramics or magnetostrictives as sensors and actuators, is also theoretical, computational and experimental.

Investigators supported under this grant have made significant progress in the past 3 years on several topics. These can be roughly divided into several distinct but related areas: (i) structural acoustic control, (ii) modeling of hepatic uptake and elimination of dioxin, and (iii) estimation of electromagnetic dispersion and geometry using incident microwave pulses. The research efforts on the latter two subjects are in close collaboration with Dr. Richard Albanese and associates in Armstrong Labs (now AFRL), Mathematical Products Division, Brooks Air Force Base. Detailed descriptions of the efforts and results can be found in the readily available publications listed in this report. Those listed as CRSC-TR are technical reports available from the Center for Research in Scientific Computation at North Carolina State University. Investigators supported in part under this grant include H.T. Banks, R.C. Smith, M. Demetriou, P. Emeric, R. Curtain, Y. Zhang, I. Groselj, T. Lin, Ric del Rosario, I. Lauko, G. Pinter, D. Rubio, R. Ravindran, D. Bortz, and B. Straughan. Additional student investigators were supported under a companion AASERT Grant AFOSR F49620-93-1-0355, for which a Final Technical Report has been previously filed with AFOSR.

I. Structural Acoustic Systems and Smart Material Actuators

Our investigation of noise suppression techniques for structural acoustic systems focused on systems in which a noise source adjacent to an elastic structure caused structural vibrations which in turn coupled with adjacent acoustic fields. While this phenomenon arises in systems ranging from transformers to aircraft fuselages, in all cases it is characterized by the transmission of energy from the structure to an acoustic medium through force and momentum coupling. Furthermore, these structural acoustic mechanisms must be fully incorporated in models, analysis and control design to attain adequate attenuation of structure-borne noise. For the applications we considered, control was obtained using smart material sensors and actuators bonded to the structure. Two specific materials which we considered were piezoceramics and and magnetostrictives.

The investigation contained significant aspects of model development, the development of numerical algorithms and convergence analysis, the development of techniques for parameter estimation and control design and ultimately, the experimental implementation of feedback control techniques. In this manner, we provided a comprehensive analysis of the problem from initial model development through experimental implementation.

The initial modeling efforts were focused on quantifying the basic mechanisms underlying the structural and acoustic components in the system, the structural acoustic coupling and the dynamics of smart material control elements bonded to the structure. For the initial investigation, piezoceramic patches bonded to the surface of the structure were employed as control actuators. Linear models incorporating both passive and active patch interactions with beams, plates and shells were developed and are summarized in [7]. In more recent work, magnetostrictive transducers have been considered as actuators in structural and structural acoustics systems which involve thick structures since the forces and strains which they produce are significantly larger than those generated by piezoceramics. To attain such outputs, however, it is necessary to employ the magnetostrictives materials at drive levels where nonlinear dynamics and hysteresis are significant. As reported in [10, 11, 18], the inherent hysteresis and nonlinearities were modeled using the domain theory of Jiles and Atherton. An alternative modeling technique based on Preisach operators as developed in [23, 24, 25] was presented in [20, 21] while nonlinear control techniques appropriate for these transducers were presented in [19, 22]. It is noted that both the linear piezoceramic models and nonlinear magnetostrictive models have been validated through extensive experiments.

Modeling techniques, numerical methods and control design for coupled structural acoustic systems were initially developed for a 2-D acoustic system driven by an adjacent Euler-Bernoulli beam. In this setting, numerical and parameter estimation techniques were studied, and LQR and H^∞ (MinMax) feedback control methods were developed and numerically tested [1, 2, 4, 8, 9]. Aspects of this work culminated in the 1994/1995 Best Paper in Structures, Structural Dynamics and Control Award which was sponsored by the Adaptive Structures and Material Systems Committee of the ASME Aerospace Division.

With the efficacy of the model-based control techniques for coupled structural acoustic systems thus established, efforts were focussed on a pair of 3-D systems modeling experimental devices at NASA Langley Research Center. The first consisted of a cylindrical hard-walled chamber with a vibrating circular plate at one end. For this system, the investigation yielded comprehensive numerical results demonstrating the manner through which the modeled physics could be used to improve compensator efficiency [3, 17]. In summary, the investigation demonstrated minimal loss of control authority for that system when employing an output feedback compensator as compared with full state LQR results. Furthermore, the study demonstrated that very adequate attenuation could be obtained via a compensator which incorporates the fully coupled model but utilizes only structural sensors. Both conclusions are important when considering the experimental implementation of the method.

The second system was comprised of a thin cylindrical shell enclosing an acoustic field. This system was employed at NASA Langley Research Center as a prototype for investigating internal sound pressure levels in a fuselage. The analysis of shell dynamics is significantly more complex than that for plates due to the coupling between inplane and bending vibrations due to the curvature. A first step in this analysis was the development of models which incorporate these curvature effects on actuator dynamics [7]. These coupling effects must also be accommodated in the numerical methods and control design. In this component of the investigation, a Galerkin method for approximating cylindrical shell dynamics was developed and tested [12]. A spline basis was employed in the axial direction and Fourier expansion were employed in the periodic circumferential direction. This approximation framework proved suitable for shells containing nonhomogeneities due to the smart material sensors and actuators and provided sufficient flexibility to encompass a variety of boundary conditions. Optimal feedback control methods employing these models and numerical techniques are reported in [13, 14]. In these papers, it is illustrated that the computation of voltages to the piezoceramic through LQR theory provides strong attenuation in all three components of the shell displacement (longitudinal, circumferential and transverse). It is also illustrated, however, that these full-order computations involve systems which often have in excess of 800 degrees of freedom; hence direct real-time experimental implementation is currently infeasible. To address this issue, reduced-order methods for approximating system dynamics and control design were considered. Our approach followed that of Ito and Ravindran who demonstrated that reasonable approximation and control results could be obtained in flow applications modeled by the Navier-Stokes equations with as few as 10 basis functions as compared with finite elements methods requiring up to 10,000 degrees of freedom [15, 16]. For our shell applications, numerical examples have demonstrated that for many regimes, the shell dynamics can be fully resolved and controlled using systems constructed with 15-30 reduced-order basis functions. This brings the systems to a range in which experimental implementation is feasible.

The final major component of this investigation concerned the experimental implementation of the PDE-based control methods. These experiments were performed with the circular plate taken from the end of the previously described structural acoustic system. The first step involved the estimation of plate and patch parameters and validation of the resulting model. As illustrated in [5], the resulting PDE model was highly accurate and would fit up to six modes over a 2500 Hz frequency range. A state estimator was developed and LQG theory was used to compute controlling voltages to a centered piezoceramic patch bonded to the plate. In both transient and steady state experiments, attenuation levels on the order of $80-90\%$ were attained [6]. These were typically within 10% of the numerically computed levels. The capability for controlling transient dynamics illustrated a significant advantage of this feedback PDE approach over the feedforward methods typically employed in acoustic applications.

II. Modeling the 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 U.S. 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 particular 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 dynamics of TCDD interaction with two intracellular proteins, the Ah receptor and cytochrome P450 1A2 [26, 27]. The resultant mathematical model is a nonlinear coupled system of partial differential equations and ordinary differential equations with time delay. We have established the well-posedness of the model [28], have developed approximation methodologies (with convergence arguments) for numerical simulation and the inverse problem, and are continuing initial promising simulation findings.

III. Estimation of Dielectric Parameters and Geometry in Electromagnetic Dispersion

Microwave images of tissue structures and soils play very important roles in many areas, including clinical and environmental medicine. These microwave images are useful in detection/enhanced treatment of abnormality of human organs and tissue, and detection/remediation of underground toxic wastes. The electromagnetic properties of a medium are generally characterized by its electric and magnetic polarization mechanisms and its static conductivity. Our recent efforts involved the development of partial differential equation (Maxwells equations) based identification techniques for dispersion in physical and biological distributed parameter systems, with those for living tissue being a special case.

Our efforts have focused on a time domain approach for the investigation of dispersion mechanisms of a medium in electromagnetic field problems. We use Maxwells equations coupled with a generalized electric polarization model in terms of a convolution of the electric field with an impulse response function. This model includes time hysteresis mechanisms as well as the usual ordinary differential equations (e.g. Debye, Lorentz and multiples of these) for dispersion. Existence, uniqueness and continuous dependence of solutions on data have been given for a one-dimensional (p-polarized plane waves) dispersive medium case in [29, 30]. Estimation of electromagnetic properties of media have been demonstrated via numerical examples. Parameters representing the electromagnetic property of a medium may include the static permittivity, relaxation time, natural frequency, static conductivity, etc. depending on the polarization model chosen.

The methodology for estimation of electromagnetic parameters has also been used as a basis for interrogation of geometry of targets. Computational efforts based on "method of mappings" techniques used in optimal shape design have verified the ability to use electromagnetic pulse probes to determine geometry as well as material dielectrics when the interrogated body has partial boundaries of supraconductive material [30]. We have recently [31] demonstrated the possiblity of use of acoustic gratings as a reflector of electromagnetic probes in determining geometry in place of the supraconductive back boundary.

IV. Vibration Based Damage Detection

As we have demonstrated in earlier AFOSR supported research [8, 32], smart structures have potential applications in NonDestructive Evaluation (NDE) of damage and in general health monitoring. Among the different types of smart material structures currently studied, structures with bonded piezoelectric ceramic patches are of particular interest. These patches can act both as actuators and sensors in a self-analyzing fashion, providing the host structure with smart material capabilities. Previous efforts [32] focused on the evaluation of symmetrical through-holes drilled in aluminum beam-like structures based on a direct time domain estimation method of spatially varying physical parameters of the structures. The model was based on the Euler-Bernoulli theory, which assumes that the center of the damage coincides with the neutral axis of the beam and the damage is symmetric with respect to this center line. To overcome the restriction produced by this special assumption of symmetry a two-dimensional model for in-plane vibrations of a cantilever plate with a non-symmetrical damage was developed for use in the context of defect identification [33]. A Galerkin method was used to approximate the dynamic response of the structures. The natural frequency shifts due to the damage were estimated numerically and compared to experimental data obtained from tests on cantilever aluminum plate-like structures damaged at different locations with defects of different depths. The damage location and extent were determined by an enhanced least square identification method. Efficacy of the frequency shift based algorithms was demonstrated using experimental data [34]. Location and severity of damage was characterized within satisfactory accuracy. Although experimental results were only obtained on aluminum samples, the framework proposed in this research effort can be applied to other metallic or composite plate-like or shell structures. This work also has direct implications in our joint investigations with AFAL scientists at Brooks AFB on vibration based health monitoring in tissues.

V. Interactions and Transitions

Under support of this grant and a companion AASERT for graduate students, substantial interactions and collaborations with Air Force scientists took place during the period of funding.

In the earlier part of the funding period, numerous collaborations with Dr. Richard Albanese and his associates, including Dr. Yun Wang, at Armstrong Labs, Brooks AFB, occured in the areas of electromagnetic dispersion and hepatic modeling of dioxin. Specific detailed collaborations occured during the following dates:

1995: Jan. 19-23 (Albanese and Wang); Feb. 22-24 (Blaschak and Wang); April 27-29 (Wang); July 13-14 (Wang); Aug. 28-30 (Wang); Oct. 26-29 (Albanese and Wang); Dec. 15-16 (Wang).

1996: April 27-30 (Albanese and Wang); June 17-19 (Wang); July 30-31 (Albanese); Aug. 6-10 (Wang); Sept. 19-21 (Albanese, Wang, Blaschak, Medine).

1997: Jan. 3-8 (Albanese); May 5-7 (Albanese).

The collaborations intensified during 1997 with the following visits:

1. June 15-August 30, 1997: C. Musante, a graduate student at NCSU, spent a 10 week summer fellowship with Albaneses group at Brooks AFB. Substantial progress was made on modeling and simulation of dioxin transport in the liver.
2. July 30-August 2, 1997: H.T. Banks visited and collaborated with Albanese and group at Brooks Air Force Base. In addition to discussions of the dioxin efforts, our progress on inverse imaging and interrogation using electromagnetic probes was discussed.
3. November 13, 1997: H.T. Banks and C. Musante visited with Jeff Fisher and colleagues in the toxicology group at Wright Patterson to discuss our progress in the dioxin modeling project.

The work on structural acoustics has led to strong ongoing collaborations with AF scientists led by Mike Stanck (Wright Patterson) and with Boeing (Seattle and St. Louis) investigators. Our efforts have led to substantial involvement in a project on cavity acoustic suppression in aircraft bays led by Mike Stanck at Wright Patterson. Our efforts were initiated via a February 14, 1997 visit H.T. Banks made to Boeing, Seattle to meet with a Dean Jacot led group (including Steve Northcroft, Mark Castilluccios, John Wei and others) where he discussed mutual interests in acoustic suppression as well as nondestructive evaluation of structures. Subsequent meetings included:

1. March 27, 28, 1997: NCSU team (H.T. Banks, K. Ito and R. del Rosario, and R.C. Smith, who at the was time at Iowa State) visited Boeing group at Seattle (Dean Jacot, et al).
2. May 22, 1997: NCSU team (H.T. Banks, R.C. Smith, C. Musante) visited with Mike Stanck and colleagues at Wright Patterson.
3. October 7, 1997: H.T. Banks visited with Jacot and Boeing team in Seattle.

4. November 6,7, 1997: H.T. Banks and D. Rubio (postdoc) visited Dean Jacot and colleagues at Boeing, Seattle. Through their help, the NCSU team subsequently acquired NXAIR from Greg Molvik at Arnold (AEDC). This code is not documented nor supported by AEDC staff. Unfortunately the NCSU team has been unable to modify this code to suit our needs and its use in the project has been abandoned for the time being.

5. November 13,14, 1997: H.T. Banks, D. Rubio, and R.C. Smith met at Wright Patterson with Mark Stanck led group including Lynn Shaw and Alan Cain (from Boeing, St. Louis). This teaming with Cain has proved most useful for the NCSU efforts.

6. February 6, 1998: Alan Cain and Ed Kerschen (one of Cains subcontractors from University of Arizona) met with group at NCSU in Raleigh. Cain is providing NCSU code related to sheer layer flow/cavity lip interaction that we feel will be most helpful in pursuing the desired modeling, control, and reduced order computational efforts.

During this period, R.C. Smith (Iowa State) permanently joined the team at NCSU on January 1, 1998. We have a strong team in place, have substantial interactions with relevant scientists, and our efforts on modeling of the nonlinear acoustics/structure interaction in the cavity problem are making significant progress.

The AFOSR supported research in this grant has led to specific and multiple collaborations with scientists at Lord Corpaoration (Dr. Lynn Yanyo, Dr. Beth Muñoz, Dr. Mark Jolly, Scott Durso, and Mike Gaitens among others). Enabling research has led to development of computational methodologies and software packages for several inverse problems involving distributed parameter systems. Projects on elastomers, magnetorheological fluids and radio frequency electromagnetic bonding of adhesives have used direct transitions of ideas developed in the context of AFOSR support through this grant. Specific application of ideas has been made in the modeling and design of rubber based elastomers to be used in automotive, aircraft, and heavy equipment vibration suppression devices. Details of some of these results are included throughout the numerous publications listed as partially supported by this grant (specifically see [35, 37, 38, 40, 42, 47, 48, 50, 51, 54, 55, 58, 59, 60]).

The electromagnetic/solid interactions efforts involve major collaborations with Dr. Richard Albanese and Dr. Yun Wang, Mathematical Products Division, Armstrong Labs, Brooks AFB. Specific collaborative discussions took place on the following dates in 1995-1996: October 26-29; December 15-16; April 27-30; June 17-19; July 30-31; and August 6-10.

VI. Publications Supported in Part Under this Grant

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