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13. ABSTRACT *(Maximum 200 words)*
This interdisciplinary research program is focused on designing and implementing robust controllers on smart structures. The primary research objectives are: (i) structural modeling of smart structures incorporating both material and geometric nonlinearities, (ii) development of controllers using conventional and neural network based algorithms, and (iii) distributed control techniques using spatially distributed sensors and actuators. We have investigated modeling techniques for structures that account for the material and geometric nonlinearities, continuity of tractions across interlaminates, hysteric behavior of the PZTs, interaction between the PZTs and the substrate, orthotropic nature of the PZTs, anisotropic properties of composite plates, and the inertia forces. A structural identification method based on the measurement of eigenvalues and eigenvectors of the structure has been developed and verified using experimental results. We have successfully designed and implemented multiobjective robust controllers as smart structures. Practical considerations and limitations of the controller implementation using neural network hardware are also investigated.

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NONLINEAR AND DISTRIBUTED CONTROL OF SMART STRUCTURES USING ARTIFICIAL NEURAL NETWORKS

Final Progress Report

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A. Statement of the Problem Studied

The primary research objectives are (i) structural modeling of smart structures incorporating both material and geometric nonlinearities, (ii) development of controllers using conventional and neural network based algorithms, and (iii) distributed control techniques using spatially distributed sensors and actuators. The design and implementation of controllers on smart structures requires mathematical representations of the system. We have investigated modeling techniques for structures that account for the material and geometric nonlinearities, continuity of tractions across interlaminates, hysteric behavior of the PZTs, interaction between the PZTs and the substrate, orthotropic nature of the PZTs, anisotropic properties of composite plates, and the inertia forces. The design of active controllers plays a very important role in the overall development of smart structures for a given application. The robust controllers were designed and implemented on smart structures for vibration suppression and mode shape control. These methodologies will minimize the effects of uncertainties on the closed-loop performance of the structural system. We have also investigated the capabilities of artificial neural networks for mathematical modeling and robust control of smart structural systems. The performance of smart structural systems is influenced by structural parameter variations, operating conditions and modeling errors. The identification methods which incorporates uncertainties were investigated. We have also developed distributed sensors for the measurement of physical quantities of the structural systems. Accomplishments in these areas are summarized below.

B. Summary of the Most Important Results

(i) Modeling of Smart Structural Systems

The modeling effort is based on (i) using the three-dimensional linear elasticity theory to analyze vibrations of a plate with PZT layers either bonded to its top and bottom surfaces or embedded in it, (ii) developing form invariant polynomial constitutive relations for nonlinear transversely isotropic and orthotropic piezoceramics, and (iii) developing a finite element code to analyze three-dimensional materially and geometrically nonlinear transient problems involving PZTs embedded in or bonded to the surfaces of a nonlinear elastic structure.

Shape Control of Plates Using Piezoceramic Elements

We have used the first-order shear deformation theory to study deformations of a rectangular plate with piezoceramic elements (PZTs) bonded symmetrically to its top and bottom surfaces and covering 19.8, 28.8, 38.4, 53 and 84% of the surface area of a 30 cm x 30 cm x 1.8 mm simply supported graphite/epoxy plate subjected to 10 N/m^2 uniformly distributed load on the top surface. It

was found (cf. Figs. 1-4) that the electric field intensity required to suppress the plate deflections decreased sharply as the surface area covered by the PZTs increased from 19.8 to 28.8% but the decrease was small for further increase in the size of PZTs. We note that the voltage required varied with the orientations of fibers in the lamina, and with its material. A feedback control algorithm was implemented and was shown to control the vibrations of the centroid of a square aluminum plate simply supported on two opposite sides and free on the other.

In contrast to the plate theory used above, we also employed the three-dimensional linear elasticity theory to analyze the vibrations of a laminated plate with the bottom and top layers consisting of PZTs. For a 40 cm x 30 cm x 1 mm graphite-epoxy plate with 0.1 mm thick PZT top and bottom layers, and essentially equal values for the maximum elastic moduli for the graphite/epoxy lamina and PZT-G1195, as should be clear from the results summarized in the following table, the attachment of PZT layers changes noticeably the natural frequencies of the composite plate.

Values of resonant frequencies Ω_{mn} for the graphite/epoxy plate as computed by the plate theory and the present method and also by the present method for the plate with PZTs bonded to the top and bottom surfaces[a]

n/m	1	2	3	Case
1	1.260	4.217	9.208	1
	1.260	4.170	9.170	2
	1.455	4.065	8.550	3
2	2.373	5.041	9.919	1
	2.330	5.040	9.880	2
	3.585	5.790	10.035	3
3	4.466	6.761	11.343	1
	4.460	6.710	11.290	2
	7.350	9.225	13.005	3

[a]Case 1, plate theory; case 2, present method, plate without PZTs; case 3, present method, plate with PZTs.

For the plate vibrating at a frequency close to one of its natural frequencies with the displacement field given by $u_3^0 = 0.3\sin(m\pi x_1/40)\sin(n\pi x_2/30)e^{\Omega_{mn}t}mm$, $u_1^0 = 0$, and a voltage $\pm V_0 e^{i\Omega_{mn}t}$ applied to a 6 cm x 6 cm square region of the top and bottom PZTs with zero voltage applied to the rest of the PZT surfaces, we determined the values of V_0 required to suppress the deflections of points on the plate diagonal as a function of the location of the centroid of the 6 cm x 6 cm region. The most effective locations, as shown in Figs. 5 and 6 of the centroid of the square PZT region are points where the amplitude of initial vibrations of the plate is maximum. The distribution of the nondimensional shear stress at the interface between the plate and the top PZT layer for the structure vibrating at a frequency close to Ω_{11} revealed high shear stress (e.g. see Fig. 7) at the edges of the

excited square region; similar results were obtained for other modes of vibration. The high value of the shear stress at a point may result in delamination of the PZT layer there.

Free Vibrations of a Linear Thermopiezoelectric Body

We have used two perturbation methods to ascertain the changes in the frequencies caused by thermal dissipation in a thermopiezoelectric body. In the first method, the solution is perturbed with respect to heat conductivity and in the second with respect to the thermopiezoelectric constants. Both methods give the relative frequency shift to be imaginary thus implying the decay of the amplitude of vibrations. In the first method adiabatic material constants are used, and in the second isothermal material constants are employed. For thickness stretch vibrations of a quartz plate, the two methods give close results: the magnitude of the shift in the relative frequency which represents the effects of thermal damping is of the order of 10^{-10}.

Nonlinear Elastroelastic Problems

Mixed variational principles in which stresses, electric field, displacements and electric potential are considered as field variables are often employed in the finite element solution of problems involving cracks or other discontinuities. We have developed various functionals and have shown that the vanishing of their first variations is equivalent to the pertinent governing equations and side conditions such as initial and boundary conditions. Thus the solution of an initial-boundary-value problem entails finding a stationary value of one of these functionals.

A finite element code capable of analyzing dynamic finite deformations of a nonlinear elastic structure with nonlinear piezoceramic elements has been developed and has been successfully debugged. The problem formulation accounts for both material and geometric nonlinearities and the applied load is an arbitrary function of time. The PZTs are assumed to be perfectly bonded to the adjoining matrix material. The coupled set of ordinary differential equations, obtained by the Galerkin approximation of the governing partial differential equations, are solved by the explicit central-difference method. However, the nonlinear algebraic equations obtained by applying the Galerkin approximation technique to the Maxwell equations with no inertia terms are solved by an implicit method. Several test cases have been run, and techniques to make the code more computationally efficient are being investigated.

(ii) Modeling and Control of Multivariable Smart Structural Systems Using Distributed Sensors

Obtaining minimal system realizations suitable for control system design can be particularly challenging for multivariable smart structural systems. The large number of closely spaced lightly damped modes hinder the modeling process making it time consuming and difficult. Parameter

variations, incorrect assumptions and inexact boundary conditions also increase the modeling difficulty. We have developed a system identification technique for the derivation of minimal, continuous time state variable models for multivariable smart structural systems. This structural identification technique is based on the measurement of eigenvalues and eigenvectors of the structural system. Unlike computational identification techniques, the availability of multiple sensors ,simplify the modeling effort and allows the implementation of full state feedback controllers with simple analog hardware circuits. The amount of hardware required for the implementation of an analog linear quadratic regulator is significantly reduced when compared with standard discrete control implementation methods. The robustness characteristics of the controllers are also retained in this method of implementation. We have developed a methodology for the generation of polyvinylidene fluoride (PVDF) film sensor arrays which measure the parametric structural quantities for system identification and feedback control (Figures 8-9).

For a general unknown distributed parameter system, the eigenvalues and eigenvectors can not be measured directly. Eigenvalues are conspicuous in the frequency domain and the eigenvectors exist at near steady state conditions. By utilizing a priori knowledge of the structural systems, we developed a method for the direct measurement of these quantities using shaped and segmented PVDF film sensors. The required shape functions are extremely simple even for complex multimember distributed parameter systems. The shape functions developed are also insensitive to parametric changes or uncertainty in the structure. Using the triangular and rectangular shaped sensors, we can measure directly structural displacement, velocity, rotation , and angular velocity of the structural parameters. Identification and control are successfully implemented on a multivariable plate system and experimental results are quite satisfactory (Figures 10-12).

The performance of smart structural system is influenced by structural parameter variations, operating conditions and modeling errors. A mathematical model of the smart structural system must include not only the nominal plant, but also the uncertainties in the system. Often information related to these uncertainties is available during the system identification process, however, most system identification techniques do not address these issues. We developed a systematic identification procedure for the incorporation of eigenvalue variations in the structural identification procedure. A minimal amount of experimental data is required for the identification of uncertainties. measurement accuracy and parameter variation information on the specific values being measured is translated into the structured uncertainty model. With the structured uncertainty modeling in place, robust control systems are designed and implemented on experimental lattice structure.

(iii) Design and Implementation of Robust Controllers

Design of Robust Controllers with Actuator Saturation

The design and implementation of robust controllers on smart structural systems is often constrained by available control force of the actuators. The Lead Zirconite Titanate (PZT) actuators which are used for the control of flexible structures have limited control authority. The performance of the system is often limited by control effort constraint instead of the closed loop stability and performance. Due to the limited availability of control effort, it is desirable to utilize all of the control force in order to obtain the best performance. We developed a procedure by integrating robust control design methodologies with constrained actuator techniques for designing controllers. In order to implement the proposed controllers, two-dimensional distributed structure, called lattice structure, is designed and fabricated. Actuation of the structure is provided by PZT actuators. Two shaped PVDF film sensors were used to measure the displacement of the structure. A mathematical model of the structure is determined using experimental test data. The model is validated using the finite element modeling techniques. The robust controllers have been designed for the structure by incorporating the structured and unstructured uncertainties in the design methodology The performance of the closed-loop system for natural frequency variations is determined experimentally. The performance and robustness properties of the controllers are satisfactory (Figures 13-14).

We have also developed methods for design of robust controllers for smart structures with multiple objective functions. This method provides a tradeoff between closed-loop performance and disturbance attenuation. We have also demonstrated the applicability of distributed sensors for the implementation of full state feedback controllers. The lattice structure experimental test article was utilized to demonstrate the uncertainty modeling and robust multiobjective control implementations.

Neural Network-Based Structural Identification and Control

The design and implementation of robust controllers on smart structural systems require a mathematical representation of the system. The structural identification method called the eigensystem realization algorithm (ERA) is used for system identification purposes. The ERA utilizes strongly measured signals for the evaluation of models and hence minimizes the inaccuracies due to measurement noise. A neural network-based procedure for determining the Markov parameters of dynamical systems from experimentally determined input-output sequences has been developed A mathematical model of the structural system is then determined from these Markov parameters using ERA (Figures 15-16). The neural network architecture for system identification utilize the standard backpropagation learning algorithm for training and are often large in size. Therefore, such networks typically require very long training times. To enhance the rate at which such networks learn and

hence reduce the learning time, we have developed an accelerated adaptive learning rate algorithm. This algorithm adjusts the learning rate used in the standard backpropogation algorithm at every epoch so as to minimize the output error at a faster rate and improve the error performance.

Feedforward and specialized feedback neural networks have found extensive application in the area of dynamical system control. In earlier studies the analytical results of these methods were verified using simulation studies only. The main limitation to real time implementation was the available hardware and computational power. We have successfully designed and implemented a neural network-based multiinput-multioutput linear quadratic Gaussian with loop transfer recovery (LQG/LTR) controller was implemented on the three mass smart structural system using PC-based data acquisition system (Figures 17-18). The next step toward implementation of neural network-based controllers is the use of Intel's electronically trainable analog neural network (ETANN) chip. This study also demonstrated successful application of the ETANN chip for robust control of smart structural systems. The cantilever plate smart structural system is used as the experimental test structure to implement a ETANN-based LQG/LTR controller. A custom interface board with analog hardware is designed and built to interface the sensor and actuator signals with the ETANN chip. The analog delay line chip manufactured by Tanner Research Inc. is used with the ETANN chip to realize the network architectures. A key feature of this study is that a single chip implementation of a robust controller has been made possible by the use of the analog neural network chip. Initially a significant difference was noticed in the behavior of a network in simulation and on the one implemented using ETANN chip. This was due to the inherent properties of the analog domain and the limitations of the chip such as weight read/write precision, non-ideal shape of the sigmoid activation function, etc. The factors involved with the implementation of the controller were systematically identified. various corrective methods were incorporated to either eliminate or minimize the anomalies in the functioning of the ETANN chip and the associated analog hardware. Then the closed loop performance of the ETANN-based single chip robust controller was in good agreement with the simulation and experimental controller (Figures 19-20).

Smart structural systems are inherently nonlinear due to material and geometrical properties and nonlinearities in sensors and actuators. These structures exhibit a linear operating region which can be controlled using linear controllers. We have utilized the ability of neural networks to map nonlinear dynamical systems to accommodate the structural nonlinearities. In addition, the adaptability property of neural networks is utilized to modify the controller in response to changing structural parameters and changes in actuators and sensors. Simulation studies of the performance of a closed loop time varying linear and nonlinear systems have been studied with and without on-line adaptation. The simulation results are very good (Figures 21-22).

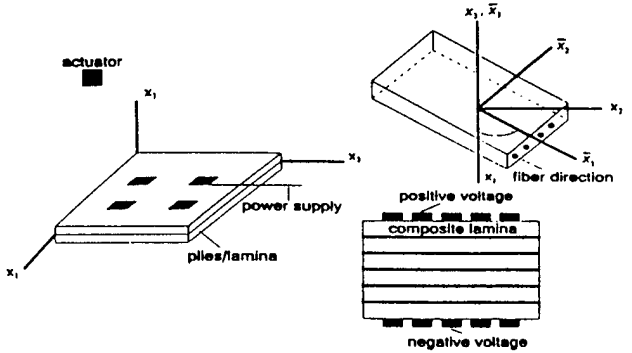

Fig. 1 Schematic sketch of the plate with PZTs.

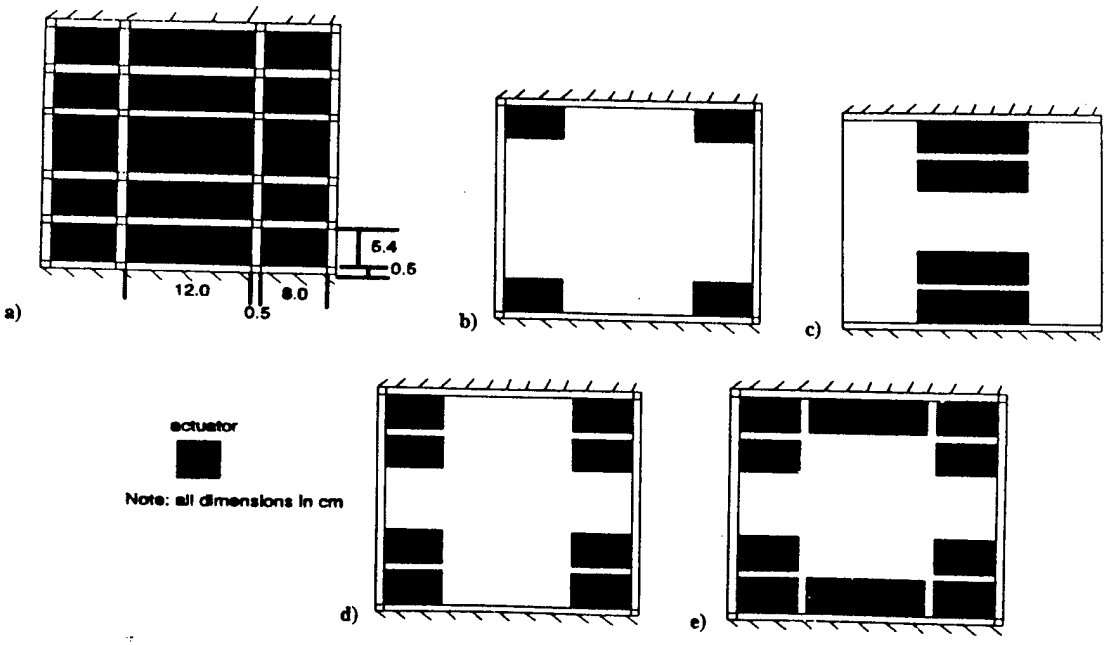

Fig. 2 Set up for the "smart" plate.

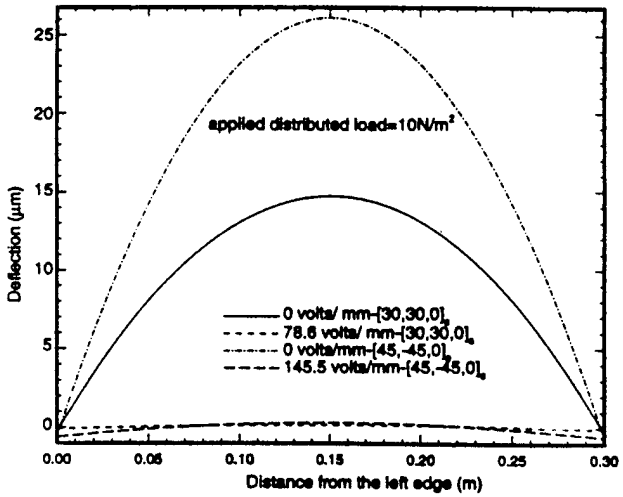

Fig. 3 Deformed shapes of the centerline of a simply supported plate for two different orientations of fibers both with and without actuators applying surface forces.

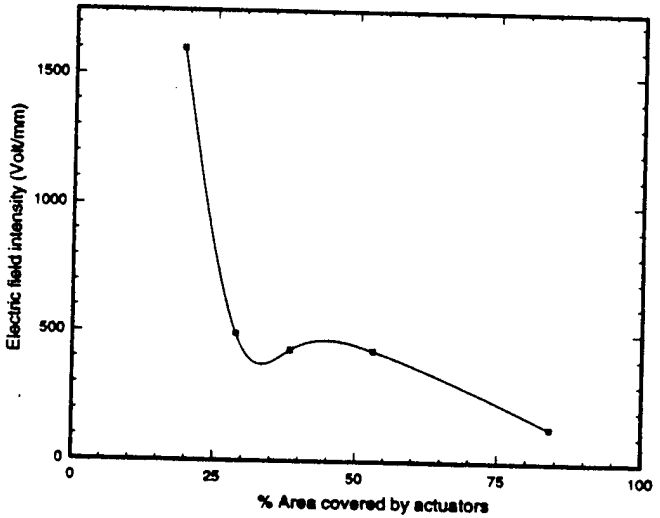

Fig. 4 Electric field intensity required to suppress the deflections of the centerline of a simply supported aluminum plate vs the surface area covered by the actuators.

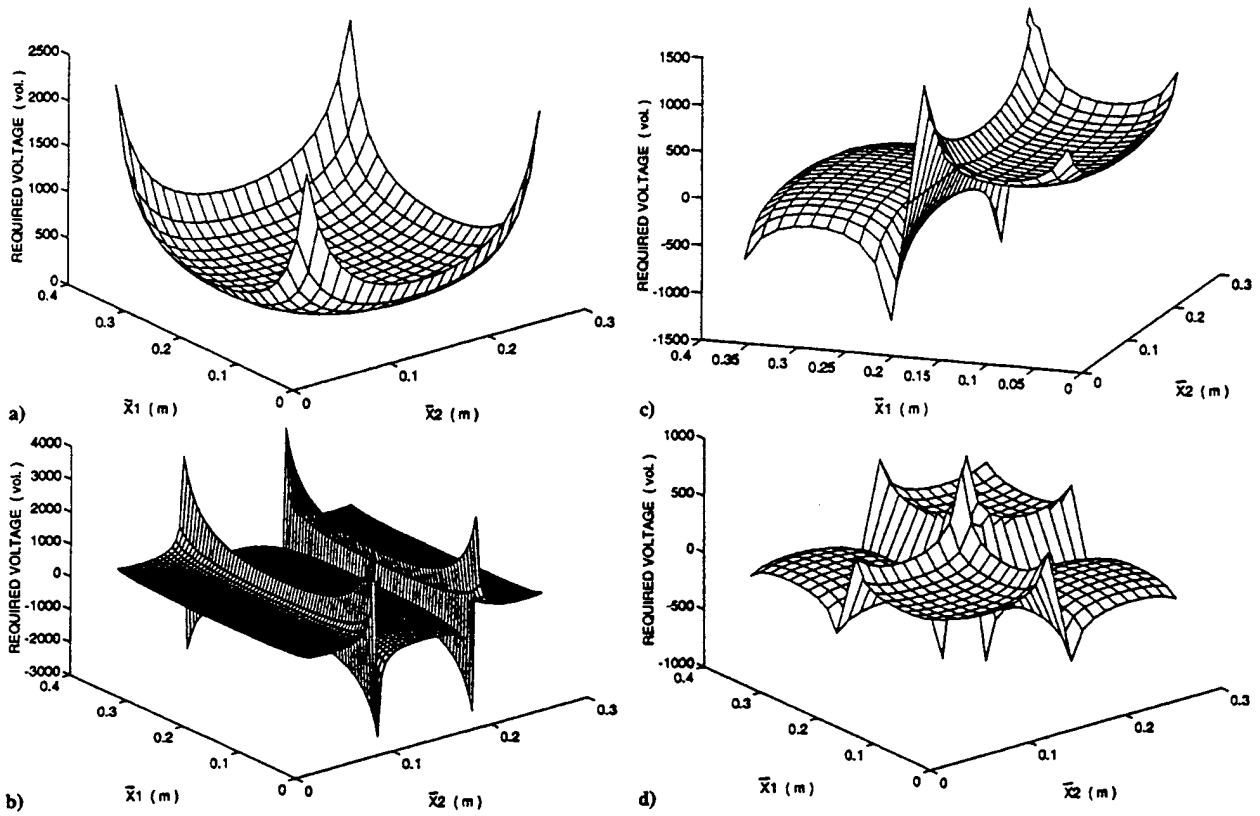

Fig. 5 Voltage required to suppress the deflections of points on the plate diagonal as a function of the location of the centroid of the 6 × 6 cm PZT region that is excited. The plate is vibrating steadily at a frequency close to a) Ω_{11}, b) Ω_{13}, c) Ω_{21}, and d) Ω_{22}.

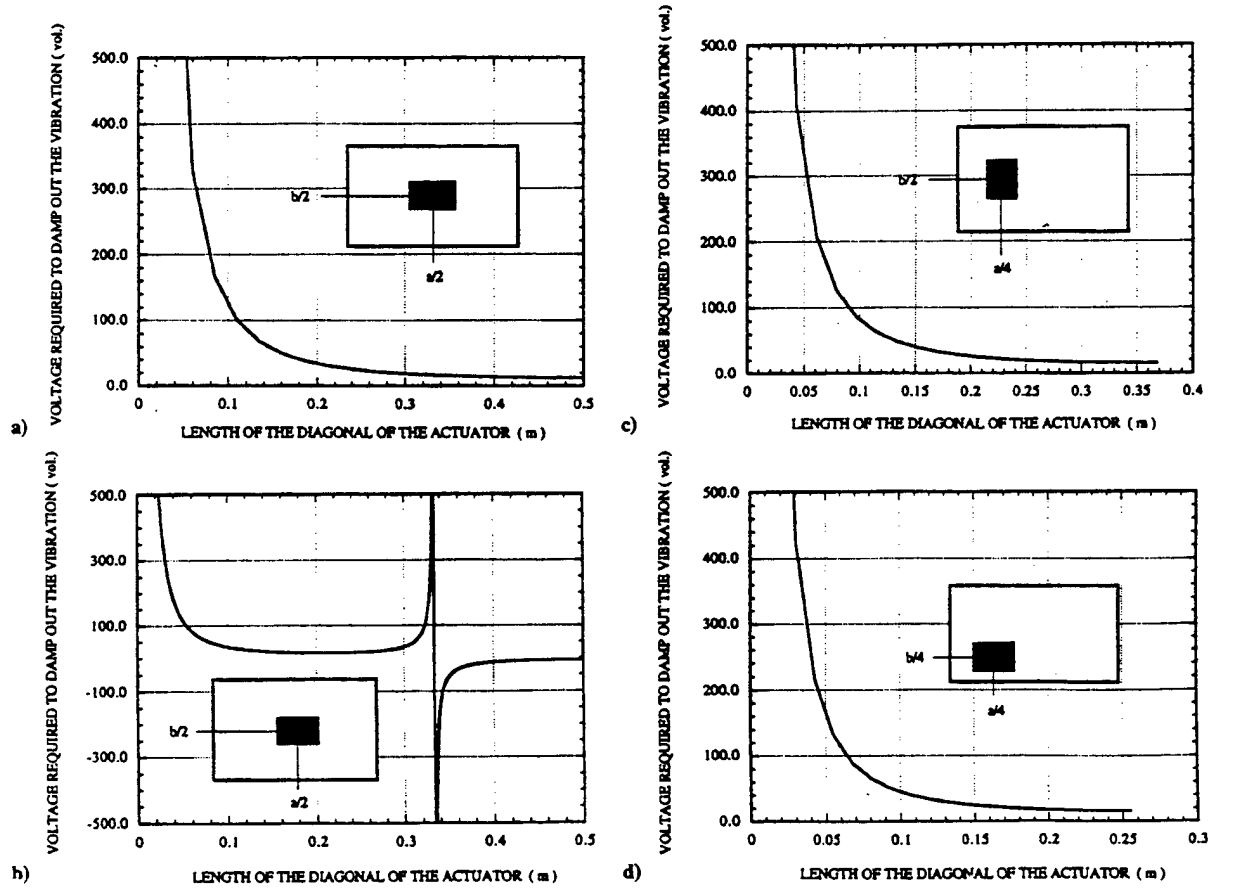

Fig. 6 Voltage required to suppress the deflections of points on the plate diagonal as a function of the length of the diagonal of the rectangular excited PZT region with its centroid located at an optimum location. The plate is steadily vibrating at a frequency close to a) Ω_{11}, b) Ω_{13}, c) Ω_{21}, and d) Ω_{22}.

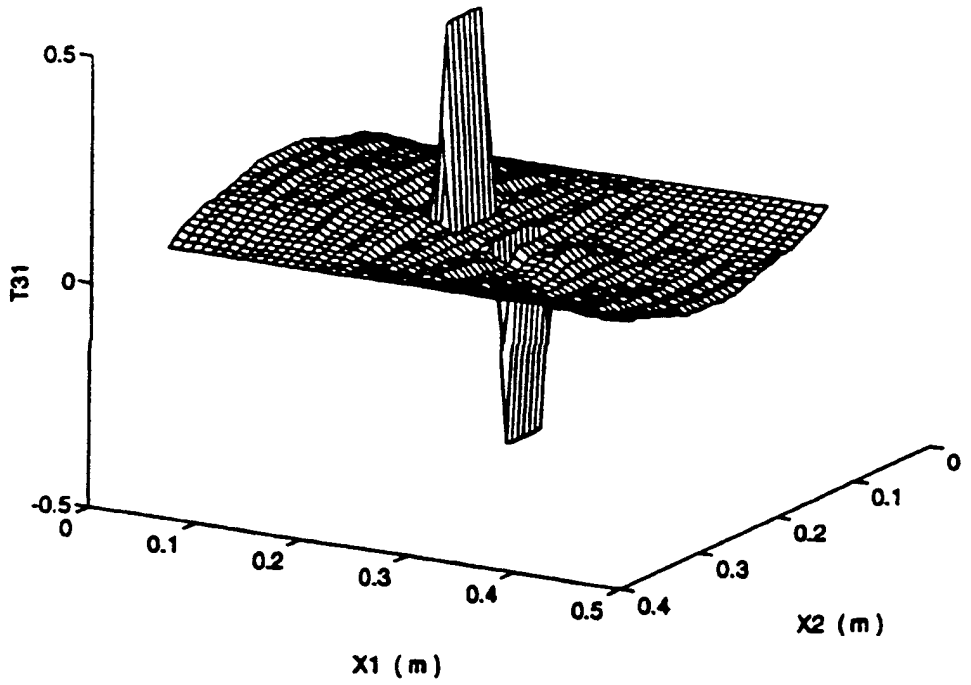

Fig. 7 Normalized shear stress $T_{31}(x_1, x_2, h) = \tau_{31}(x_1, x_2, h)\, h^b / e_{31}^b \bar{V}^b$ under the top actuator for Ω near Ω_{11}.

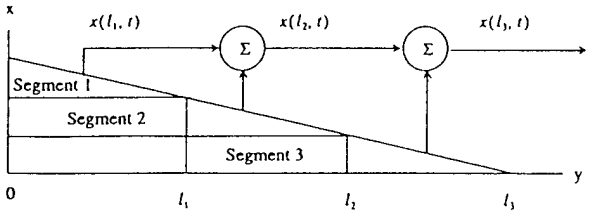

Figure 8. Segmented PVDF film.

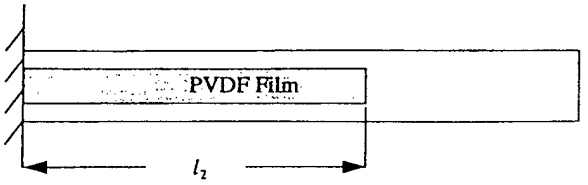

Figure 9. Cantilever beam with uniformly shaped PVDF film sensor.

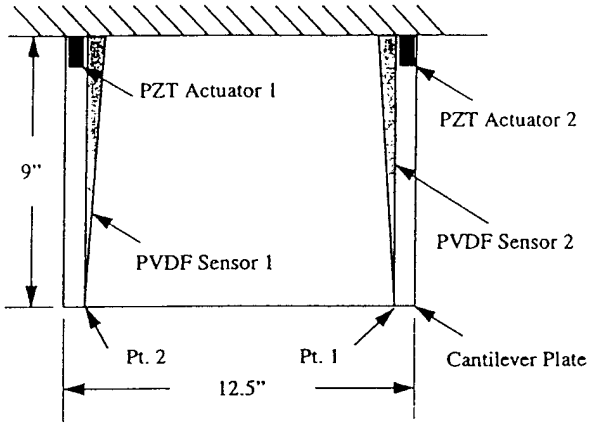

Figure 10 Cantilever plate test article.

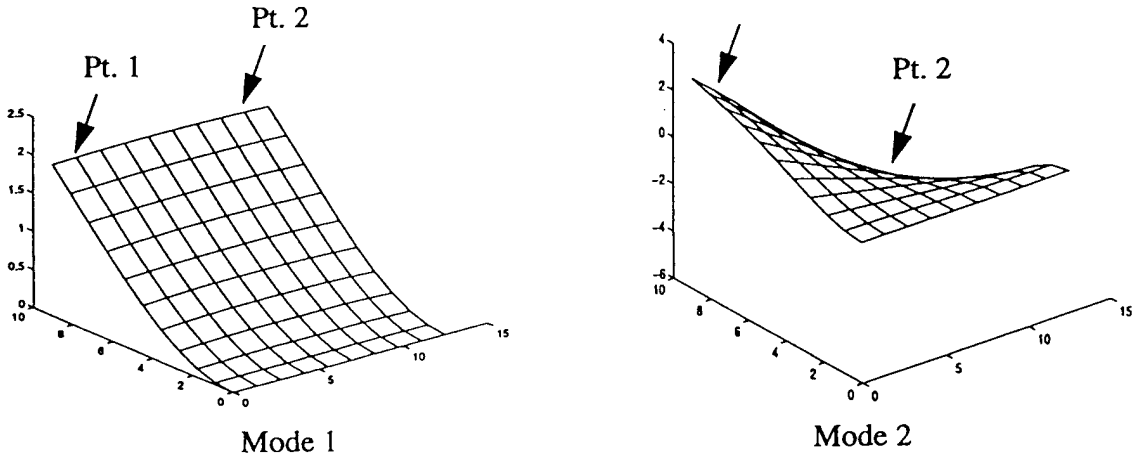

Figure 11 Plate mode shapes.

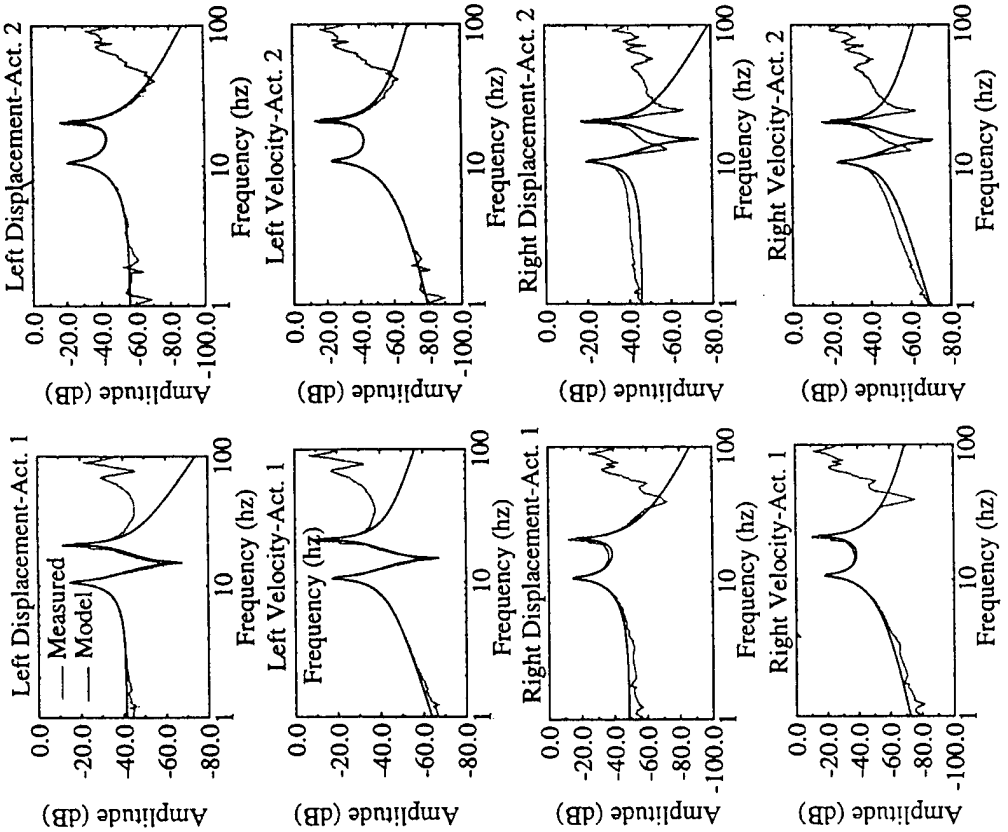

Figure 12. Structural system frequency response.

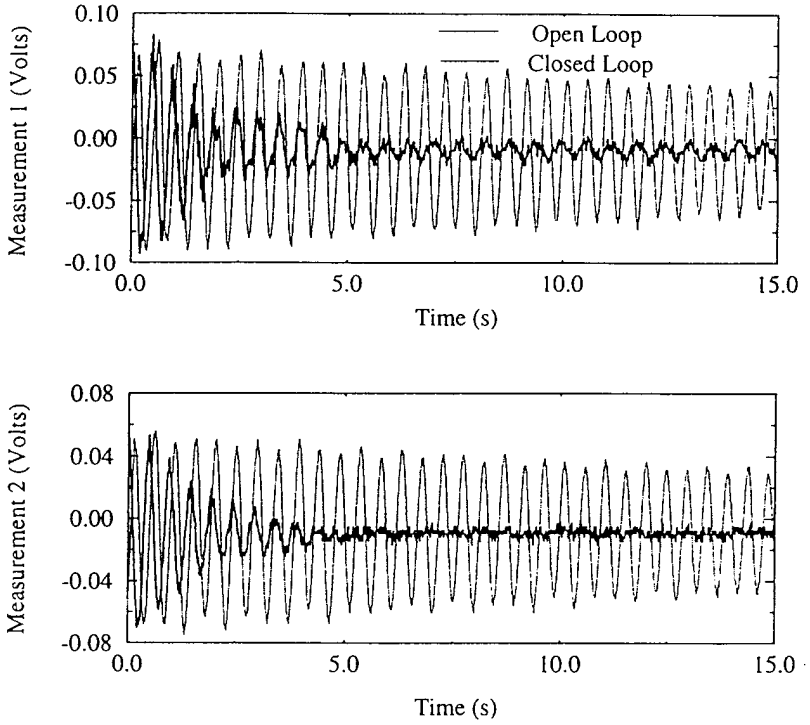

Figure 13 Mode 2 Robustness Test

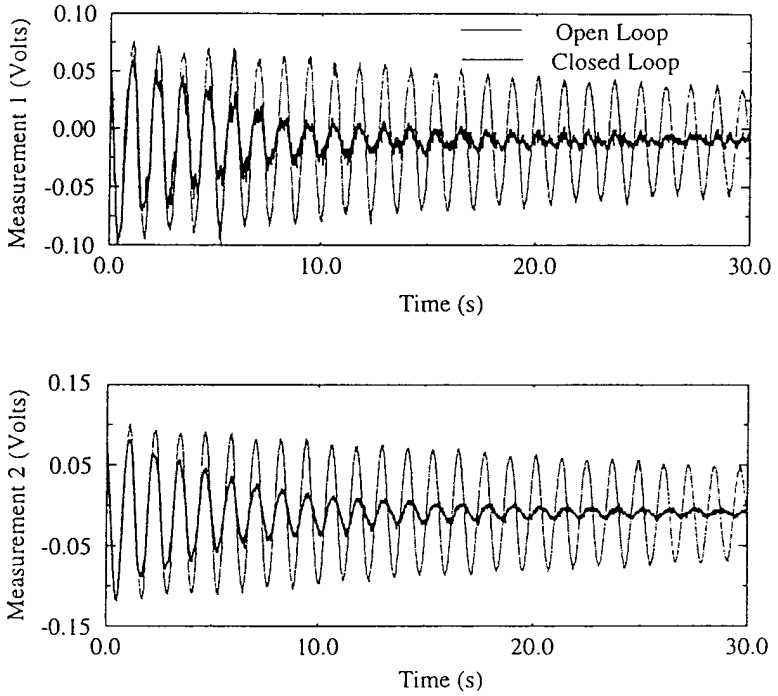

Figure 14 Mode 1 Robustness Test

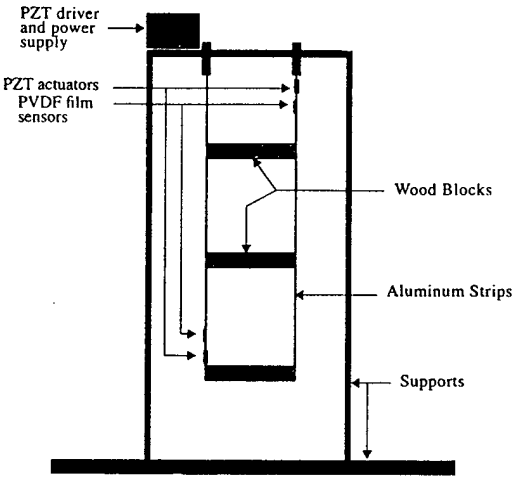

Figure 15 Three mass structure: PZT actuators.

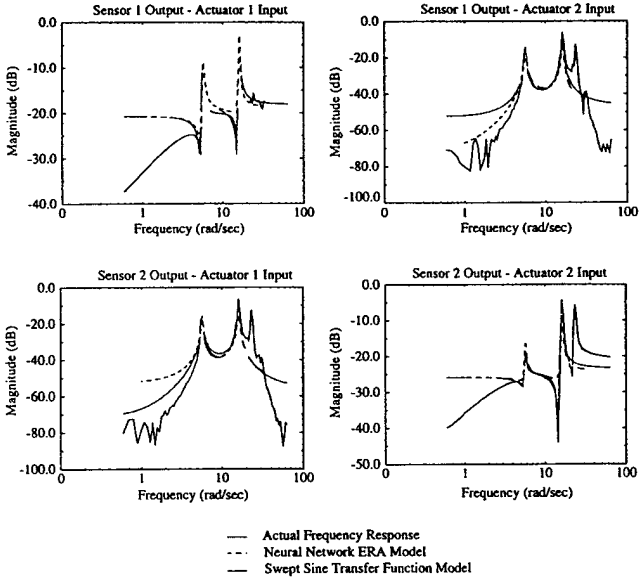

Figure 16 Frequency responses: Three mass structure with PZT actuators. Reprinted by permission of Technomic Publishing Co., Inc.

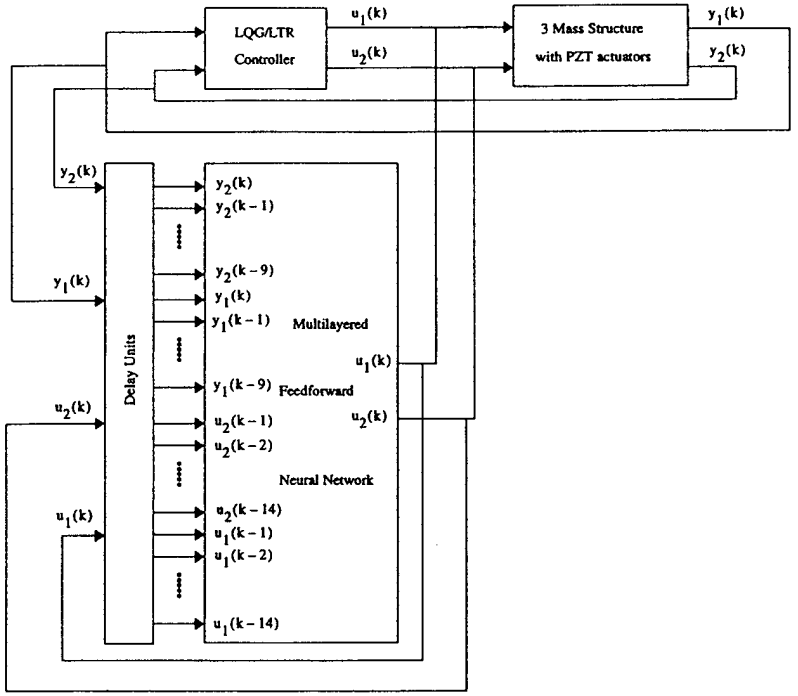

Figure 17 Architecture of neural network-based LQG/LTR controller. Reprinted by permission of Technomic Publishing Co., Inc.

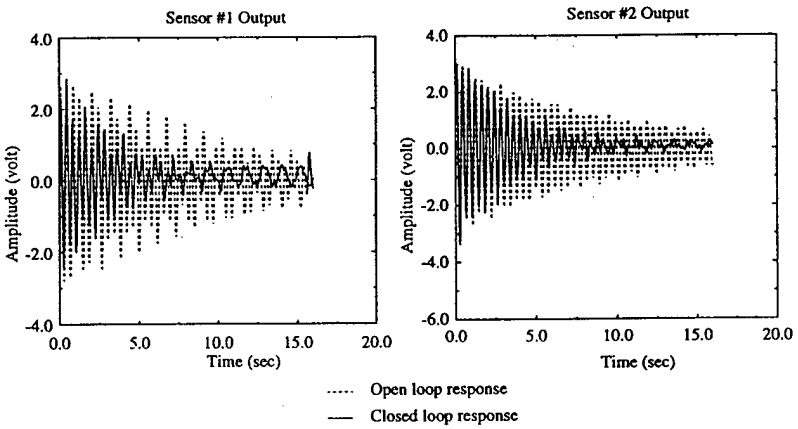

Figure 18 Neural network-based LQG/LTR controller response. Reprinted by permission of Technomic Publishing Co., Inc.

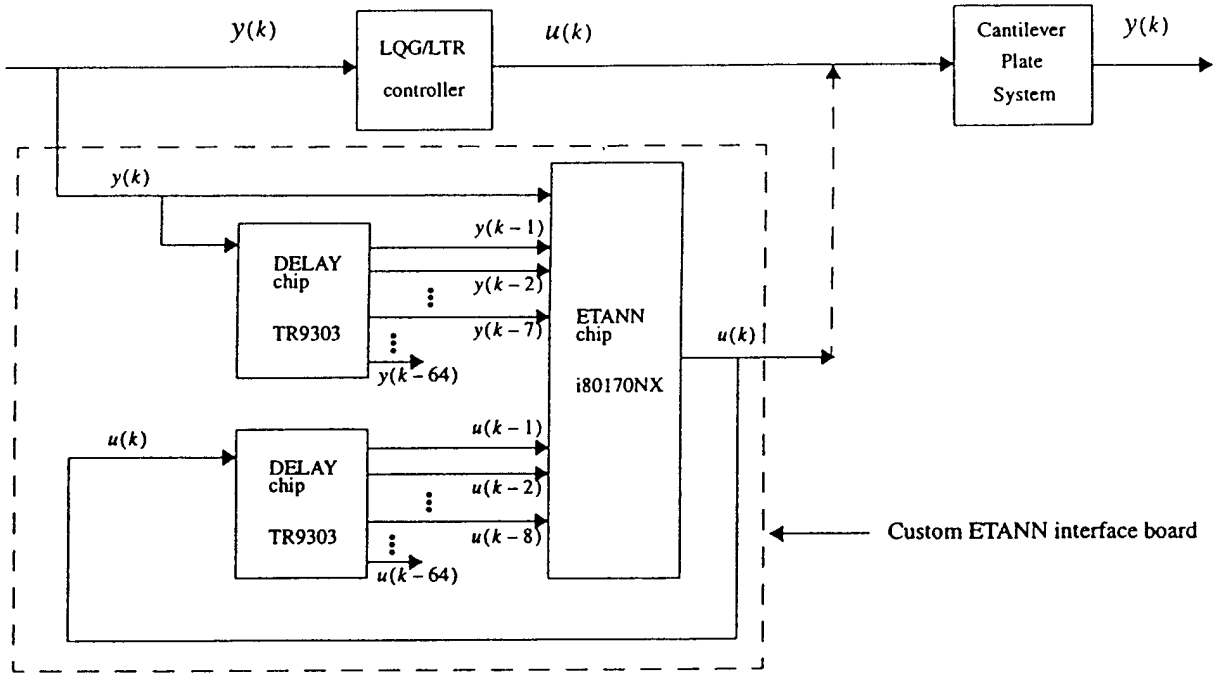

Figure 19 ETANN LQG/LTR controller setup using Model IV.

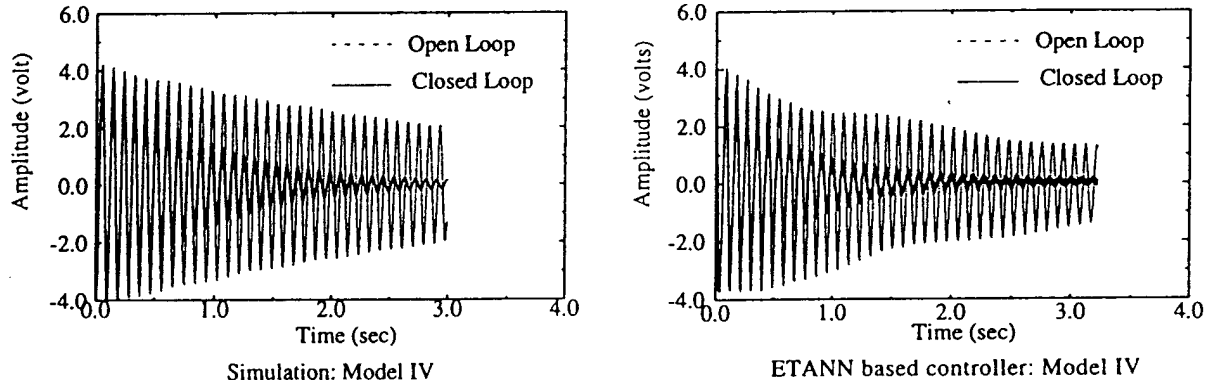

Figure 20 Comparison of LQG/LTR implementations using Model IV.

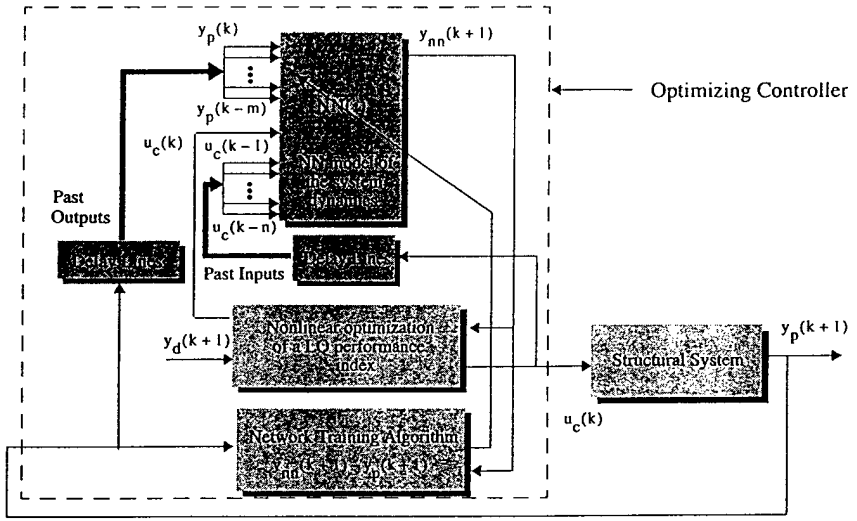

Figure 21 Neural network based controller block diagram.

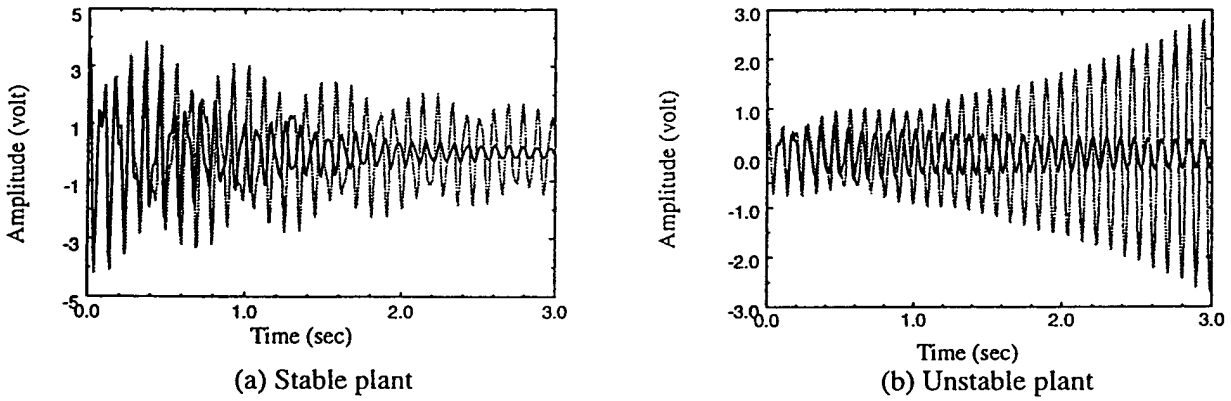

Figure 22 Closed loop versus open loop response: linear plant. (a) Stable plant. (b) Unstable plant.

C. List of All Publications and Technical Reports

Refereed Journals

1. J.S. Yang and R.C. Batra, "Free Vibrations of a Piezoelectric Body," *J. Elasticity,* **34,** 239-254, 1994.
2. J.S. Yang and R.C. Batra, "A Theory of Electroded Thin Thermopiezoelectric Plates Subject to Large Driving Voltages," *J. Appl. Physics,* **76,** 5411-5417, 1994.
3. J.S. Yang, R.C. Batra and X.Q. Liang, "The Cylindrical Bending Vibrations of a Laminated Elastic Plate Due to Piezoelectric Actuators," *Smart Materials & Structures,* **3,** 485-493, 1994.
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