01 Jan 1995

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Recommended Citation

F. J. Kern et al., "System Modeling and Control of Smart Structures," *Proceedings of the 1995 American Control Conference*, Institute of Electrical and Electronics Engineers (IEEE), Jan 1995.
The definitive version is available at https://doi.org/10.1109/ACC.1995.520911

Proceedings of the
American Control Conference
Seattle, Washington • June 1995

SYSTEM MODELING AND CONTROL OF SMART STRUCTURES

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Abstract

This paper presents multidisciplinary research and curriculum efforts at the University of Missouri-Rolla in the smart structures area. The primary objective of our project is to integrate research results with curriculum development for the benefit of students in electrical, and mechanical and aerospace engineering and engineering mechanics. The approach to the accomplishment of curriculum objectives is the development of a two-course sequence in the smart structures area with an integrated laboratory. The research portion of the project addresses structural identification and robust control methods for smart structures. A brief summary of the research results and a description of curriculum development in the smart structures area are described in this paper.

1. Introduction

The field of smart structures encompasses several technologies that enable flexible structures to sense and control their own geometric, environmental and structural characteristics to achieve high performance and self-diagnostic capabilities. The design and implementation of smart composite structures necessitates the integration of (i) modeling and fabrication of composite structures, (ii) advances in sensor and actuator technology, (iii) advanced control methodology, and (iv) artificial neural networks. The smart structures is one of several areas of engineering where research results, which have been compartmentalized in several different engineering disciplines, must be integrated into a functional unit because the applications cross disciplinary boundaries. At the University of Missouri-Rolla, an interdisciplinary curriculum in smart structures is being developed under the Combined Research-Curriculum Development program of the National Science Foundation.

The research portion of the project addresses structural identification and robust control methods for smart structures. Ongoing research efforts are aimed at developing robust control techniques for structural systems using modal space decompositions, mixed H_2/H_∞ controllers for natural frequency uncertainties, neural network based structural identification methods, and the development of smart structural test articles. This paper will briefly review the results obtained so far [6-14].

The primary objective of our project is to integrate research results with curriculum development in the multidisciplinary area of smart structures for the benefit of students in Electrical, Mechanical and Aerospace Engineering, and Engineering Mechanics. The curriculum development objectives are (i) the introduction of smart structures concepts to senior undergraduate and graduate students, (ii) the development of interdisciplinary educational experience, and (iii) the enhancement of the design component of curriculum and capstone design projects.

We developed a two-course sequence integrated with a multidisciplinary laboratory in smart structures. The first course, entitled "Introduction to Smart Structures," was offered during the 1994 spring semester and was open to both graduate and senior undergraduate students. The students were divided into two groups for remedial work. The EE students were provided with an overview of mechanics of materials, mechanical vibrations, and finite element methods. The ME/AE students got remedial work on such topics as linear system theory, MATLAB control software, and sampled-data systems. The other topics covered were smart sensors and actuators, advanced topics in mechanical vibrations, composite structures, and identification and control techniques. The second course, entitled "Control of Smart Structures," was offered during the 1994 fall semester and is open to graduate students only. The topics included in this course are structural control techniques, adaptive control systems, active and passive damping using piezoceramic actuators, modeling and control of distributed sensors, and neural networks for smart structures. Some of the laboratory experiments are introduction to PC-based data acquisition systems, transfer function analyzers, and MATLAB software, vibration control of simple smart cantilever beam and 3-mass structural systems.

Both courses are team taught with one professor from the Department of Electrical Engineering and one from the Department of Mechanical and Aerospace Engineering. We wish to share the experience in teaching multidisciplinary courses in smart structures. In this paper, we will give details of these courses along with a typical laboratory experiment.

2. A Brief Summary of Research Results

The application of both piezoelectric (PZT) and shape memory alloy (SMA) materials as sensors and actuators in the active control of smart structures has been extensively reported in the literature [1-14]. We are conducting research on various aspects of smart structures, however, in this paper a brief summary of modeling and robust control of smart structures is presented.

(a) Finite Element Modeling and Analysis of Smart Structures

Active control systems that rely on piezoelectric materials are effective in controlling the structural response. Piezoelectric materials which exhibit mechanical deformation when an electric field is applied and conversely, generate a change in response to mechanical deformation can be used as actuators and sensors, respectively. Modeling and simulation will play a key role in the design of smart structures.

Recent developments in modeling aspects of reinforced composite structures containing piezoelectric materials can be seen in references [3-5]. Crawley and Lazarus [3] developed a consistent plate model which considers the actuators to be plies of a laminated plate. Lee [4] presented a mathematical model that incorporates piezoelectric effect into the classical laminated plate theory. The theory developed is capable of modeling the sensing and actuating behavior of a laminate. Wang and Rogers [5] applied the classical laminated plate theory to a laminated plate with spatially distributed actuators. They used Heaviside functions to model the presence of piezoceramic patches. They neglected the actuator patches in calculating the global properties of the laminate. All the existing composite plate formulations are based on the classical plate theory. However, it is well established that in the analysis of composite plates, a theory which includes shear deformation is required.

A mathematical model based on a shear deformation theory for the analysis of laminated plates with piezoelectric sensors and actuators is developed at the University of Missouri-Rolla [6]. The piezoelectric sensors and actuators can be surface bonded or embedded and can be either continuous or segmented. The model takes into account the mass and the stiffness of the piezoelectric patches. Based on the model presented in reference [6], finite element models have been developed for the vibration and buckling control of laminated composite plates with integrated piezoelectric sensors and actuators [7-9]. In comparison to the existing models, the present finite element model does not introduce the voltage as an additional degree of freedom. Secondly, one need not explicitly consider the Heaviside functions and their derivatives which have been used to analytically model the effect of the patch over the plate. Following is an overview of the results presented in references [7-9].

The finite element code developed [7] is validated with surface-bonded actuators subjected to a static electric field with the results reported in reference [3]. A wide variety of case studies is then performed to study the effectiveness of piezoceramics in actively controlling the transient response of composite plates. It is found that the mass and stiffness of the piezoceramic patches has a significant influence on the transient response of the system. Both negative-velocity feedback and positive-position feedback gains are used to achieve vibration control.

We have also developed a finite element code to study the dynamic buckling behavior of laminated plates subjected to a linearly increasing uniaxial compressive load [8]. The sensor output is used to determine the input to the actuator using a proportional control algorithm. The forces induced by the piezoelectric actuators under the applied voltage enhance the critical buckling load. Finite element solutions are presented for composite plates with clamped and simply supported boundary conditions and the effectiveness of piezoelectric materials in enhancing the buckling loads is demonstrated.

A finite element code [9] is developed for the active control of thermally induced vibration of laminated plates with piezoelectric sensors and actuators. The formulation is based on a thermoelastic version of the piezoelectric based laminated constitutive equations. The model takes into account the mass, stiffness, and the thermal expansion of the piezoelectric patches. The influence of stacking sequence, boundary conditions, and the size of the piezoceramic patches on the thermally induced response of laminated plate is studied. The results presented in the paper illustrate the potential value of integrating the piezoelectric materials into composite structures under thermomechanical loadings.

(b) Structural Identification Techniques

The mathematical model of a structural system can be obtained either using physical properties of the system or using structural identification methods. The process of constructing a model to describe the vibration properties of a structure based on experimental test data is known as structural identification. The identification techniques which simultaneously process data from multi-input/multi-output systems under non-ideal noisy conditions are investigated. We have adapted the eigensystem realization algorithm (ERA) for determining the models of smart structures. One of the limitations with the ERA method is the difficulty associated with the measurement of Markov parameters of the system.

Most neural network identification techniques generate a neuro-model of a system such that the network response is similar to that of the system response for a given input. These neuro-models of systems cannot be used to design feedback controllers using modern control techniques since no information about the parameters of the linear system are available. In 1991 Chow and Yam suggested a method to identify a mathematical model of a system from its input output data. This method requires the knowledge of the values of the transfer function coefficients within a certain range for training the neural network. This assumption seriously limits the applicability of this method to real world problems because there is seldom any information available about the model of a system.

Two different neural network based identification methods have been successfully utilized to develop state space models of a structural system from experimental test data.

(c) Neural Network Technique to Generate the Markov Parameters

This method was suggested by Bialasiewicz et al. [10] in which a multilayered neural network was used to estimate the Markov parameters (pulse response) of a system from experimental random input-output data. The ERA algorithm can then be used to obtain a state model of the system from the Markov parameters. In this algorithm a multilayered neural network is trained using the experimentally collected input output data of a structural system. Once the network is trained, the neurons can be assumed to be operating in their linear range within a certain range of the input signals. The required Markov parameters are found to be proportional to the product of the weighting matrices of the network.

In this method, a feedforward neural network is trained using the experimental input output data and the states of the system. The inputs to the neural network at every iteration is the plant inputs and the states at that time instant, and the desired outputs of the network are the outputs of the plant and the states of the system at the next time instant. The inputs and the desired outputs of the network can then be written as

$$U_{nn}(k) = \begin{bmatrix} x_1(k) \\ x_2(k) \\ \cdots \\ x_n(k) \\ u_1(k) \\ \cdots \\ u_m(k) \end{bmatrix} \qquad Y_{nn}(k) = \begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ \cdots \\ x_n(k+1) \\ y_1(k) \\ \cdots \\ y_q(k) \end{bmatrix}$$

where U_{nn} and Y_{nn} are the input and the desired output vectors of the network.

After the training is complete, the product of the weighting matrices can be partitioned into the state space matrices of the system as given by equation

$$[w3 \times w2 \times w1] = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

where $w3$, $w2$ and $w1$ are the trained weights of the network and *A*, *B*, *C* and *D* are the system matrices.

(d) Robust Control of Smart Structures

The design and implementation of control strategies for large, smart structures presents challenging problems. To demonstrate the capabilities of shape-memory-alloy actuators, we have designed and fabricated a three-mass test article with multiple shape-memory-alloy (NiTiNOL) actuators. The force and moment actuators were implemented on the structure to examine the effects of control structure interaction and to increase actuation force. These SMA actuators exhibit nonlinear effects due to deadband and saturation. The first step in the modeling process was the experimental determination of the transfer function matrix derived from frequency response data. A minimal state space representation was determined based on this transfer function matrix. Finally, in order to reduce the order of the controller, a reduced order state space model was derived from the minimal state space representation. The simplified analytical models are compared with models developed by structural identification techniques based on vibration test data.

From the reduced order model, a controller was designed to dampen vibrations in the test bed. To minimize the effects of uncertainties on the closed-loop system performance of smart structures, a LQG/LTR control methodology has been utilized. An initial standard LQG/LTR controller was designed; however, this controller could not achieve the desired performance robustness due to saturation effects. Therefore, a modified LQG/LTR design methodology was implemented to accommodate for the limited control force provided by the actuators. The closed-loop system response of the multiple input-multiple output (MIMO) test article with robustness verification has been experimentally obtained and presented in the paper. The modified LQG/LTR controller demonstrated performance and stability robustness to both sensor noise and parameter variations. We have also employed H2/H infinity optimal control methods for the design of robust controllers [11-14].

3. Curriculum Development in Smart Structures

The primary objective of our effort has been to integrate research results with curriculum development in the cross-disciplinary area of smart structures. The first course entitled "Introduction to Smart Structures" was first given during the 1994 Spring Semester and was open to both graduate and senior-undergraduate students from both EE and ME/AE departments. Most of the students were graduate students. Laboratory work was required as part of the course.

(a) Course outline of "Introduction to Smart Structures"

(i) Overview of Smart Structures (one week)

(ii) Remedial Work (3 weeks)

After the first week, the students were divided into two groups for remedial work. The EE students were given a brief survey of ME topics such as review of mechanics of materials, finite element methods, and introduction to mechanical vibrations. The remedial work for the students whose background is not in electrical engineering consisted of a review of Fourier transforms, linear systems, controller design methods, basics of sampling selection and data acquisition systems.

(iii) Sensors and Actuators (3 weeks)

(iv) Advanced Topics in Mechanical Vibrations (2 weeks)

(v) Composite Structures (2 weeks)

(vi) Identification Techniques (3 weeks)

(b) Course outline of "Control of Smart Structures"

The second course, entitled "Control of Smart Structures," was offered during the 1994 fall semester and was open to graduate students from the Departments of Electrical Engineering, Mechanical Engineering and Aerospace Engineering and Engineering Mechanics. This course is jointly taught with one instructor from the Department of Electrical Engineering and one from the Department of Mechanical and Aerospace Engineering. A list of the topics covered in this course is given below.

(i) Review of smart sensors and actuators and active vibration control methodologies
(ii) Active damping using piezoceramics
(iii) Control of lumped-parameter systems
(iv) Modeling and control of distributed structures
(v) Adaptive control systems
(vi) Neural networks for smart structures

4. Laboratory Experiments

The laboratory experiences were designed primarily to enhance the student's understanding of the theoretical concepts involved rather than to train them in a particular laboratory procedure or technique. The experiments described gave each student a basic understanding of the phenomenon being illustrated. Some of the later experiments also familiarized the student with the use of commercially-available analyzers and software that is commonly used in modeling and modal analysis.

The experiments were designed to be conducted by teams that had at least one electrical engineer and one mechanical engineer as a member. The idea was, of course, that the electrical engineer will be more familiar with the use of such standard laboratory equipment as digital voltmeters, signal generators, oscilloscopes, and signal analyzers while the mechanical engineer will be more familiar with the character of mechanical vibrations and will be more experienced at making measurements on mechanical systems. At least one member of the team had to be very comfortable with the use of IBM-PC compatible computers and should have been proficient in the use of at least one compiler, preferably C^{++}.

5. Student Assessment of First Course

The general reaction of the students was positive. They especially enjoyed the experimental work and liked the interdisciplinary nature of the material. Because of the extensive amount of theory that had to be developed, several students remarked about there being "too much material" and that the pace was too fast. The biggest criticism was the lack of a textbook, but those few books that were available were judged to be unsuitable for use as a text. Instead, the faculty wrote their own notes. The comments of the students will be used to improve the courses the next time that they will be offered, probably during the '95-96 school year.

6. Lessons Learned and Conclusions

- Need good class materials and textbook
- Need more time in the laboratory
- Students liked the team teaching
- Courses were very useful from research point of view
- The faculty enjoyed teaching/learning these courses.

7. Acknowledgments

This research is supported by a grant from the National Science Foundation (Grant #EEC-9315199). The support and technical interest of Dr. Win Aung is gratefully acknowledged.

8. References

[1] R. Ikegami, D.G. Wilson, J.R. Anderson and G. Julien, "Active Vibration Control Using NiTiNOL and Piezoelectric Ceramics," Journal of Intelligent Materials, Systems and Structures, Vol. 1, pp. 189-206, April 1990.

[2] A. Baz, K. Imam and J. McCoy, "Active Vibration Control of Flexible Beams Using Shape Memory Actuators," ASME Journal of Sound and Vibration, pp. 437-456, 1990.

[3] E.F. Crawley and K.B. Lazarus, "Induced Strain Actuation of Isotropic and Anisotropic Plates," AIAA Journal, Vol. 29, pp. 944-951, 1991.

[4] C.K. Lee, "Theory of Laminated Piezoelectric Plates for the Design of Distributed Sensors/Actuators. Part I: Governing Equations and Reciprocal Relationships," Journal of Acoustical Society of America, Vol. 89, pp. 1144-1158, 1990.

[5] B.T. Wang and C.A. Rogers, "Laminated Plate Theory for Spatially Distributed Induced Strain Actuators," Journal of Composite Materials, Vol. 25, pp. 433-452, 1991.

[6] K. Chandrashekhara and A. Agarwal, "Dynamic Modeling of Piezoelectric Laminated Plates," in Smart Structures and Intelligent Systems (Edited by N. W. Hagood and G. J. Knowles), Vol. 1917, pp. 451-460, Proceedings of the SPIE North American Conference on Smart Materials, Albuquerque, NM, Feb. 1-4, 1993.

[7] K. Chandrashekhara and A. Agarwal, "Active Vibration Control of Laminated Composite Plates Using Piezoelectric Devices," Journal of Intelligent Material Systems and Structures, Vol. 4, pp. 496-508, 1993.

[8] K. Chandrashekhara and K. Bhatia, "Active Buckling Control of Smart Composite Plates," Smart Materials and Structures, Vol. 2, pp .31-39, 1993.

[9] K. Chandrashekhara and R. Tenneti, "Thermomechanical Modeling of Laminated Plates with Piezoelectric Sensors and Actuators," Smart Structures and Intelligent Systems (Edited by N. W. Hagood), Vol. 2190, pp. 782-789, Proceedings of SPIE North American Conference on Smart Structures and Materials, Orlando, FL, Feb. 14-16, 1994.

[10] J.T. Bialasiewicz and D. Soloway, "Neural Network Modeling of Dynamical Systems," Proc. of International Symposium on Intelligent Control, pp. 500-505, 1990.

[11] V. Rao, "Combined Research-Curriculum Development in Smart Structures," NSF Workshop on Project Impact: Disseminating Innovation in Undergraduate Education, Washington, D.C., 1994.

[12] R. Damle, R, Lashlee, V. Rao, and F. Kern, "Identification and Robust Control of Smart Structures Using Artificial Neural Networks," International Journal on Smart Materials and Structures, Vol. 3, No. 1, pp. 35-46, 1994.

[13] V. Rao, R. Damle, C. Tebbe, and F. Kern, "The Adaptive Control of Smart Structures Using Neural Networks," International Journal on Smart Materials and Structures, Vol. 3, No. 3, pp. 354-366, 1994.

[14] R. Lashlee, R. Butler, V. Rao, and F. Kern, "Robust Control of Flexible Structures Using Multiple Shape Memory Alloy Actuators," Journal of Intelligent Material Systems and Structures, Vol. 5, No. 5, pp. 702-712, 1994.