Sheridon grating to a maximum blaze wavelength of 250 nm, although precluding its use in visible Raman systems, does not hinder its application to UV Raman or fluorescence spectroscopy because maximum grating efficiency is desirable around 250 nm. Using a Sheridon grating in a spectrograph used for UV laser combustion diagnostics reduces or eliminates the need for Rayleigh/Mie scattering filtering and thus provides more sensitivity in detecting Raman or fluorescence signals lying close in wavelength to the laser line.

Acknowledgment

This work was supported by the National Research Council through a Senior Research Associateship for the author at the NASA Marshall Space Flight Center, Huntsville, Alabama.

References

[1]Rothe, E. W., and Andresen, P., "Application of Tunable Excimer Lasers to Combustion Diagnostics: A Review," *Applied Optics*, Vol. 36, No. 18, 1997, pp. 3971–4033.

[2]Frank, J. H., Lyons, K. M., Marran, D. F., Long, M. B., Stårner, S. H., and Bilger, R. W., "Mixture Fraction Imaging in Turbulent Nonpremixed Hydrocarbon Flames," *Twenty-Fifth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1995, pp. 1159–1164.

[3]Schefer, R. W., Namazian, M., and Kelley, J., "CH, OH, and CH_4 Concentration Measurements in a Lifted Turbulent-Jet Flame," *Twenty-Third Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1990, pp. 669–676.

[4]"Optical Filter Catalog," 2nd ed., Corion Corp., Franklin, MA, 1998.

[5]Nandula, S. P., Brown, T. M., Pitz, R. W., and DeBarber, P. A., "Single-Pulse, Simultaneous Multipoint Multispecies Raman Measurements in Turbulent Nonpremixed Jet Flames," *Optics Letters*, Vol. 19, No. 6, 1994, pp. 414–416.

[6]Reckers, W., Hüwel, L., Grünefeld, G., and Andresen, P., "Spatially Resolved Multispecies and Temperature Analysis in Hydrogen Flames," *Applied Optics*, Vol. 32, No. 6, 1993, pp. 907–918.

[7]Chen, Y.-C., and Mansour, M. S., "Measurements of the Detailed Flame Structure in Turbulent H_2–Air Jet Diffusion Flames with Line-Raman/Rayleigh/LIPF-OH Technique," *Twenty-Sixth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1996, pp. 97–103.

[8]Tacke, M. M., Cheng, T. C., Hassel, E. P., and Janicka, J., "Study of Swirling Recirculating Hydrogen Diffusion Flame Using UV Raman Spectroscopy," *Twenty-Sixth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1996, pp. 169–175.

[9]Brockhinke, A., Andresen, P., and Kohse-Höinghaus, K., "Contribution to the Analysis of Temporal and Spatial Structures Near the Lift-Off Region of a Turbulent Hydrogen Diffusion Flame," *Twenty-Sixth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1996, pp. 153–159.

[10]Grünefeld, G., Beushausen, V., Andresen, P., and Hentschel, W., "Spatially Resolved Raman Scattering for Multi-Species and Temperature Analysis in Technically Applied Combustion Systems: Spray Flame and Four-Cylinder In-Line Engine," *Applied Physics B*, Vol. 58, No. 4, 1994, pp. 333–342.

[11]Wehrmeyer, J. A., Cramer, J. M., Eskridge, R. H., and Dobson, C. C., "Ultraviolet Raman Diagnostics for Rocket Engine Injector Development," AIAA Paper 97-2843, July 1997.

[12]Lerner, J. M., and Thevenon, A., *The Optics of Spectroscopy—A Tutorial*, Instruments SA, Inc., Metuchen, NJ, 1986, p. 6.

[13]Loewen, E. G., "Diffraction Gratings, Ruled and Holographic," *Applied Optics and Optical Engineering*, edited by R. R. Shannon and J. C. Wyant, Vol. 9, Academic, New York, 1983, pp. 33–71.

[14]Palmer, C. P., *Diffraction Grating Handbook*, 2nd ed., Milton Roy Co., Rochester, NY, 1994, pp. 15–19.

[15]Wehrmeyer, J. A., Cheng, T.-S., and Pitz, R. W., "Raman Scattering Measurements in Flames Using a Tunable Excimer Laser," *Applied Optics*, Vol. 31, No. 10, 1992, pp. 1495–1504.

[16]Andresen, P., Bath, A., Gröger, W., Lülf, H. W., Meijer, G., and ter Meulen, J. J., "Laser-Induced Fluorescence with Tunable Excimer Lasers as a Possible Method for Instantaneous Temperature Field Measurements at High Pressures: Checks with an Atmospheric Flame," *Applied Optics*, Vol. 27, No. 2, 1988, pp. 365–378.

R. P. Lucht
Associate Editor

Shape Control of Laminated Plates with Piezoelectric Actuators Including Stress-Stiffening Effects

Sérgio Frascino Müller de Almeida*
Instituto Tecnológico de Aeronáutica, 12228-900 São José dos Campos, Brazil

I. Introduction

PIEZOELECTRIC elements can be used as sensors or actuators in applications such as shape control, active damping, and acoustic noise suppression of a wide class of structures. The effective use of these systems requires accurate electromechanical models to simulate the interaction between the structure and the piezoelectric elements. The literature addresses the modeling of piezoelectric elements either bonded or embedded to several different types of structures. The piezoelectric actuation of beams was treated in depth by Crawley and Anderson[1] and Crawley and de Luis.[2] Several other formulations were also developed for the modeling of plates[3,4] and general shells.[5] Most of the electromechanical models proposed in the literature are based on linear analyses.

The piezoelectric elements are usually mounted to the top and bottom surfaces of a structural element and may induce in-plane extension, bending, and localized shear deformations in structural elements.[6] If both elements are actuators and shear deformation is neglected, the in-phase actuation produces in-plane deformations, whereas out-of-phase actuation produces bending. If one of the piezoelectric elements is used as an actuator while the second one is used as a sensor, or if a single piezoelectric actuator is mounted on a surface, the actuation always results in combined in-plane and bending stresses.

The in-plane stresses may have a significant influence on the mechanical behavior of plates. Initial and/or residual stresses affect the flexural stiffness and in turn the dynamic and stability characteristics of laminated plates.[7] The initial and/or residual stresses in a plate may result from a combination of boundary constraints with external applied loads and environmental effects. Almeida and Hansen[8] showed that, with proper design, thermal residual stresses caused by the curing process can be tailored to enhance the mechanical behavior of composite plates. Rammerstorfer[9] determined optimum fields of residual stresses that maximize the first natural frequency and buckling load of plates.

Piezoelectric elements provide great flexibility in inducing in-plane stress fields because the distribution and magnitude of the in-plane stresses can be easily controlled by varying the voltages applied to each actuator. The objective of this work is to investigate the effectiveness of using piezoelectric elements to control the flexural stiffness of composite plates by inducing in-plane stresses. A finite element approach is used to model laminated plates with piezoelectric actuators and/or sensors placed at arbitrary portions of the plate. The analysis assumes ideal linear theory for the piezoelectric actuation and includes stress-stiffness effects. In the case of plates without membrane-bending coupling, the in-plane problem and the bending problem may be independently solved from two subsequent linear analyses. The numeric results on the shape control of laminated plates with piezoelectric actuators demonstrate that even if the plate is unconstrained the piezoelectrically induced in-plane stresses may significantly affect the mechanical behavior of the plate.

II. Problem Formulation

Consider a laminated plate with piezoelectric elements symmetrically bonded to the top and bottom surfaces at arbitrary positions.

Received 25 May 1998; revision received 15 March 1999; accepted for publication 16 March 1999.

*Professor, Department of Mechanical Engineering.

cases the plate buckles for voltages considerably lower than the breakdown voltage limits. The relative values of the displacements presented in Fig. 1 show that the plate loses stability according to different modes whether there are tensile or compressive in-plane piezoelectric stresses. Of course, larger values of v_0 are needed to buckle the plate for larger values of thickness. Considering that the voltage applied to the actuator is limited to the breakdown voltage, the effect of stress stiffening is more pronounced for thin plates.

Figure 2 shows that the configuration with the piezoelectric elements forming a frame around the perimeter of the plate presents a behavior similar to that of the plate with two longitudinal actuators along the edges (Fig. 1), but the stress-stiffening effect is more pronounced. For compressive in-plane piezoelectric actuation, the plate stiffness decreases until it loses stability for a relatively low voltage (about −70 V). Tensile actuation initially causes the plate stiffness to increase, but the plate loses stability according to a different mode at an actuation voltage of about 100 V.

V. Conclusion

The numerical results on the shape control of laminated plates with piezoelectric actuators demonstrate that even if the plate is unconstrained the piezoelectrically induced in-plane stresses may significantly affect the mechanical behavior of the plate. Therefore, for the case of combined in-phase and out-of-phase piezoelectric actuation, accurate modeling of composite plates with piezoelectric elements should account for the stress-stiffening effects. The importance of the stress-stiffness effect depends on the magnitude of the in-phase actuation and geometric arrangement of the piezoelectric actuators, boundary conditions, geometry of the problem, and material properties.

The ability of controlling the plate stiffness has potentially interesting applications in smart structures. For example, piezoelectric actuation systems may be designed to tune the vibration frequencies of composite plates. Also, the problem of buckling control of composite plates with piezoelectric elements can be properly modeled using the present formulation.

Acknowledgment

The author acknowledges CNPq (Brazilian National Research Council) for the financial support received for this work under Grant 300219/90-3.

References

[1]Crawley, E. F., and Anderson, E. H., "Detailed Models of Piezoceramic Actuation of Beams," *Journal of Intelligent Material Systems and Structures*, Vol. 1, No. 1, 1990, pp. 4–25.

[2]Crawley, E. F., and de Luis, J., "Use of the Piezoelectric Actuators as Elements of Intelligent Structures," *AIAA Journal*, Vol. 25, No. 10, 1987, pp. 1373–1385.

[3]Ha, S. K., Keilers, C., and Chang, F.-K., "Finite Element Analysis of Composite Structures Containing Distributed Piezoceramic Sensors and Actuators," *AIAA Journal*, Vol. 30, No. 3, 1992, pp. 772–780.

[4]Batra, R. C., Liang, X. Q., and Yang, J. S., "Shape Control of Vibrating Simply Supported Rectangular Plates," *AIAA Journal*, Vol. 34, No. 1, 1996, pp. 116–122.

[5]Tzou, H. S., and Ye, R., "Analysis of Piezoelastic Structures with Laminated Piezoelectric Triangle Shell Elements," *AIAA Journal*, Vol. 34, No. 1, 1996, pp. 110–115.

[6]Chandra, R., and Chopra, I., "Structural Modeling of Composite Beams with Induced-Strain Actuators," *AIAA Journal*, Vol. 31, No. 9, 1993, pp. 1692–1701.

[7]Yang, I. H., and Shieh, J. A., "Vibrations of Initially Stressed Thick Rectangular Orthotropic Plates," *Journal of Sound and Vibration*, Vol. 119, No. 3, 1987, pp. 545–558.

[8]Almeida, S. F. M., and Hansen, J. S., "Enhanced Elastic Buckling Loads of Composite Plates with Tailored Thermal Residual Stresses," *Journal of Applied Mechanics*, Vol. 64, No. 4, 1997, pp. 772–780.

[9]Rammerstorfer, F. G., "Increase of the First Natural Frequency and Buckling Load of Plates by Optimal Fields of Initial Stresses," *Acta Mechanica*, Vol. 27, No. 1–4, 1977, pp. 217–238.

[10]Heppler, G. R., and Hansen, J. S., "A Mindlin Element for Thick and Deep Shells," *Computer Methods in Applied Mechanics and Engineering*, Vol. 54, No. 1, 1986, pp. 21–47.

[11]Oguamanam, D. C. D., Almeida, S. F. M., and Hansen, J. S., "Stress Stiffening Effects in Laminated Beams with Piezoelectric Actuators," *Journal of Intelligent Material Systems and Structures*, Vol. 9, No. 2, 1999, pp. 137–145.

A. Chattopadhyay
Associate Editor

Coevolutionary Approaches to Structural Optimization

Min-Jea Tahk*
Korea Advanced Institute of Science and Technology, Taejon 305-701, Republic of Korea
Youdan Kim†
Seoul National University, Seoul 151-742, Republic of Korea
and
Changho Nam‡
Hankook Aviation University, Kyonggi 412-791, Republic of Korea

Introduction

NONGRADIENT methods such as genetic algorithms have been applied to solve structural optimization problems with promising results.[1–4] Nonetheless, these evolutionary algorithms have not been fully developed to handle constrained optimization.[5] Until recently, all existing methods were based on the evolution of a single group. Based on the evolution of two groups with opposite objectives, a coevolution method has been devised for solving saddle-point problems.[6] This method finds two major application areas: min/max design and constrained optimization. For a constrained problem, the optimal values of the parameter and multiplier vectors correspond to the saddle point of the associated Lagrangian if a certain convexity assumption is satisfied. Hence, constrained optimization problems can be reformulated as saddle-point problems. For nonconvex problems, augmentation of the Lagrangian function provides the necessary convexity, as with the deterministic augmented Lagrangian methods. The new coevolution method has been applied to the well-known truss problems: the 10-bar, 25-bar, and 72-bar truss problems treated in Refs. 7 and 8. The numerical results clearly show that the coevolution method has good potential for large-scale structural optimization. The basic concept of the coevolution method and its application to the 72-bar truss problem are summarized here.

Coevolution for Constrained Optimization

A general constrained optimization problem is written as follows:

$$\min_x f(x), \qquad x \in \mathcal{S} \tag{1}$$

subject to

$$g_i(x) \le 0, \qquad i = 1, \ldots, m \tag{2}$$

$$h_j(x) = 0, \qquad j = 1, \ldots, l \tag{3}$$

Received 6 October 1998; revision received 25 March 1999; accepted for publication 25 March 1999.

*Associate Professor, Department of Aerospace Engineering, 373-1 Kusong Yusong. Senior Member AIAA.

†Associate Professor, Department of Aerospace Engineering. Senior Member AIAA.

‡Associate Professor, Department of Aeronautical and Mechanical Engineering, Koyang. Senior Member AIAA.