ACTIVE VIBRATION CONTROL OF SMART PLATES AND SHELLS CONSIDERING PIEZOELECTRIC NONLINEARITY

by

MOHD. YAQOOB YASIN

Department of Applied Mechanics

Submitted

in fulfillment of the requirements of

the degree of

Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2013

Certificate

This is to certify that the thesis entitled "**Active Vibration Control of Smart Plates and Shells Considering Piezoelectric Nonlinearity**" being submitted by **Mohd. Yaqoob Yasin** to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy in Applied Mechanics is a record of original bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

Prof. Santosh Kapuria
Department of Applied Mechanics
Indian Institute of Technology Delhi
New Delhi 110016

Acknowledgements

I express my heartiest gratitude and sincere thanks to my esteemed supervisor Prof. S. Kapuria for his contributions of invaluable time, eminent ideas, motivational approach, informative and illuminative guidance throughout the entire period of my work. In fact these words are insufficient to express the gratefulness to my supervisor without whom, this work would have remained a dream for me. I wish to express my sincere thanks to Dr. Obaid Iqbal Asim, Faroza Khatoon, Dr. Naushad Alam, and Prof. Suhail Ahmad, who were my teachers/mentors and whose pieces of advice guided my journey from school to this place.

I wish to give my special thanks to Dr. P. Kumari, Dr. J.K. Nath, and Dr. S.D Kulkarni for their interesting and meaningful discussions and kind help during the entire period of my work. I would like to extend very special thanks to all my colleagues and friends Arshad, Asif Sami, Aswani, Asjad, Ankur, Chaman, Ibrahim, Jitender, Kausar, Kiran, Prince, Rajneesh, Shahid, Shivdayal, Nilamber, Yudhast for their wonderful company and help during this work. I wish to express my gratitude to all the staff of the Department of Applied Mechanics for their generous help during the course of this work.

I would like to thank my parents for their love, moral support and encouragement. This thesis is the result of their constant prayer and sacrifices.

M. Yaqoob Yasin

Abstract

Increasing demand for the development of lightweight structures particularly in aerospace, automobile and space applications has brought active vibration control of structures into the focus of research in recent times. Experiments have shown that piezoceramic materials exhibit constitutive nonlinearity, when the electric field exceeds the coercive limit. Analysis and design of smart structures made of composite and sandwich laminates integrated with distributed piezoelectric sensors and actuators for achieving vibration control require a computationally efficient and accurate model for the laminate mechanics, its appropriate numerical implementation and a suitable control algorithm, all incorporating the piezoelectric nonlinearity.

In this thesis, a new electromechanically coupled efficient layerwise finite element (FE) model is developed for the analysis of smart piezoelectric multilayered shallow shells considering the nonlinear behavior of piezoelectric materials under strong electric field. The nonlinearity is modeled using the rotationally invariant nonlinear constitutive equations, with the assumption of large electric field and small strains. For the laminate mechanics, an efficient coupled zigzag theory (ZIGT) is developed for the doubly curved shallow hybrid shells. The theory considers the normal deformation in the piezoelectric layers due to transverse piezoelectric coefficient d_{33}, without introducing additional deflection variables. A consistent quadratic variation of the electric potential across the piezoelectric layers with the provision of satisfying the equipotential condition of electroded surfaces is adopted. A quadrilateral shallow shell element with four kinetic nodes and one electric node is developed. The electric node conveniently enforces the equipotential condition over a number of elements under an electrode, and also leads to significant reduction in the number of electric DOF. In spite of the requirement of C^1 continuity of the ZIGT, interpolation functions very similar to the isoparametric shape functions in C^0 formulations are used for the rotation variables using the improved discrete Kirchhoff quadrilat-

eral technique, which makes it suitable for standard FE programming. The governing equations of motion are derived using the extended Hamilton's principle for piezoelectric solids. For the static analysis, the equations are solved using the direct iteration method. For active vibration control, the FE model is transformed to the reduced order modal space considering the first few modes, and is expressed in the state space format. The resulting nonlinear control problem is solved using the feedback linearization approach.

Since such an element did not exist even for elastic laminated shallow shells, the new element is first critically assessed for its accuracy for static and free vibration responses of elastic laminated shells. This is followed by its assessment for the linear and nonlinear static responses under electro-mechanical loading, free vibration and active vibration control study of smart plates and shallow shell structures. The element has only seven kinematic degrees of freedom per node, and does not need any discretization in the thickness direction. Yet, its predictions are very close to the analytical three-dimensional (3D) piezoelasticity solutions or a detailed 3D FE analysis, for elastic as well as hybrid shells made of not only single-material composite substrates, but also sandwich substrates with soft core for which the equivalent single layer (ESL) theories with the same or higher number of primary variables perform very badly. A separate efficient ZIGT FE model with two kinetic nodes and one electric node is also developed for active vibration control study of smart piezoelectric laminated beams.

The constant gain velocity feedback (CGVF) control, optimal LQR and LQG control as well as clipped optimal control strategies are studied under step, impulse as well as harmonic excitations. Case studies on CGVF control are performed to show the instability phenomena in closed-loop response with conventionally collocated actuator-sensor pairs, and a truly collocated arrangement to remove the instability is illustrated. The effectiveness of directional actuation and sensing capability of piezoelectric composites for vibration suppression is studied. The effect of prescribing a cutoff for actuation potential is studied, and the optimum cutoff voltage which yields the control performance similar to the case of no cutoff voltage is presented. The nonlinear model is validated in comparison with the experimental data available in the literature. The effect of the piezoelectric nonlinearity on the static response and deflection/stress control is studied. Finally, the effect of piezoelectric nonlinearity on the peak control voltage required to achieve a given settling time for the vibration amplitude is studied for smart plates and shells.

Contents