Development of Comprehensive Modeling Techniques for Smart Composite Structures

Summary of Research

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Objectives

(1) Development of a completely coupled thermo-piezoelectric-mechanical theory for the analysis of composite laminates with segmented and distributed piezoelectric sensors/actuators. The model will address the two-way coupling effects between all fields accurately

(2) Development of smart composite model to analyze the interaction between piezoelectric transducers and the primary structures. The higher order displacement theory will be used to capture the transverse shear effects in anisotropic composites. The higher order descriptions of electrical and temperature fields will be developed to address piezoelectric behavior accurately.

(3) Investigation of interaction between piezoelectric actuators/sensors and primary structures using the developed model considering comprehensive loading, mechanical, thermal and electrical. Finite element technique will be used to address arbitrary geometry and boundary conditions. The effects on the structural static and dynamic response due to the thermo-piezoelectric-mechanical coupling will be investigate deeply.

(4) Investigation of the coupled structures/controls interaction problem and the control authority using the developed model to study the complex trade-offs associated with the coupled problem.

Approach

A new smart composite laminate model using the coupled thermal-piezoelectric-mechanical (t-p-m) theory is developed to investigate the behavior of multifield coupling due to segmented and distributed piezoelectric actuators. The model addresses structural response under various kinds of loading conditions, mechanical, thermal and electrical. The higher order displacement theory, which can accurately capture the transverse shear effects in the laminated composites, is used to model structural behavior of arbitrary thickness. Thus, the theory has the ability of characterizing in-plane warping and traction free boundary conditions while rendering computational efficiency. To provide more accurate evaluation of coupling effects due to electrical and thermal loading as well as the interaction between all fields, the temperature and electrical fields are modeled using higher order descriptions, which can accurately satisfy the surface boundary conditions of heat flux and electrical potential. The proposed theory is applied to investigate laminated plates with surface bonded piezoelectric actuators and sensors under comprehensive loading conditions. Finite element technique is employed to address general geometry and boundary conditions. Numerical solution is obtained to investigate the coupling effects, control authority and the interactions between piezoelectric materials and primary structures.

Results

The investigation of piezoelectric actuation effects using the developed coupled t-p-m model and the uncoupled model is conducted on a cantilevered rectangular fiber-reinforced laminated composite plate with surface bonded piezoelectric actuators at the center of top and bottom surfaces of the plate. Both top and bottom actuators are subjected to a step voltage load of same magnitude but opposite directions, making out-of-plane deformation dominant. In this case, the t-p-m model for actuators represents two-way mechanical-piezoelectric coupling (piezoelectric and converse piezoelectric effects) while the uncoupled model represents only one-way mechanical-piezoelectric coupling (converse piezoelectric effect). The steady state deflections along plate length due to a piezoelectric actuation of 50V are presented in Fig. 1. The uncoupled model overpredicts the structural deformation compared to the t-p-m model. This is because the transformation of mechanical energy into thermal and electric energies due to two-way coupling effect is neglected in the uncoupled model. In open loop conditions, coupling effects decrease steady state deflection due to the interaction between thermal, piezoelectric and mechanical fields. The deviation between the two theories will vary with structural configurations and material properties. Larger piezoelectric coupling coefficients and actuator-to-plate thickness ratios imply more coupling energy stored in piezoelectric materials, resulting in more deviation between the predictions from the two models. The developed coupled theory will therefore be more appropriate in the modeling of newly developed high-actuation materials. Figure 2 presents the total charge accumulated on the actuator surfaces. The coupled theory shows equal amount of charge on the top and the bottom electrodes. However, the uncoupled theory presents different charge values on the actuator surfaces, violating the conservative charge law. This is due to the incorrect assumption of equal electric field in the uncoupled model.

The self-sensing PZT actuator is considered to analyze the impact of two-way coupling on control authority. Figure 3 presents the ratio of equivalent modal structural damping due to control between the t-p-m model and the uncoupled model if rate feedback control is employed and only the first bending mode is excited. For gain values of 50 and 100, the damping in the t-p-m model is 0.786 and 1.378 times that obtained using the uncoupled model, respectively. This indicates that, in closed loop control, the uncoupled model overestimates control authority with low gain value and underestimates control authority with high gain value. It is due to the fact that control authority is determined by the electrical signal received by actuators and the mechanical force due to the signal. For the two cases with different gain values, initially, the uncoupled theory produces smaller displacement because it has larger ability to correct deflection with a certain piezoelectric actuation. On the other hand, this also implies that the actuators receive smaller electrical signal due to smaller displacement in the uncoupled model, which weakens its control ability. The result of combining these two opposite effects is determined by gain value. For the uncoupled model, if gain value is small, the effect of strengthening control authority is dominant and the uncoupled theory overestimates control authority. If gain value is large, the effect of weakening control authority is dominant and the uncoupled theory underestimates control authority.

The thermal coupling effects is also investigated using a uniform step heat flux applied on the top surface of the plate. Figure 4 presents the time history of the tip displacement until steady state is reached. No significant difference between the two models is observed in the dynamic response decay. However, a smaller steady state tip deflection is observed with the t-p-m model due to the fact that the t-p-m model considers all coupling effects between thermal, piezoelectric and mechanical fields while the uncoupled model considers only the coupling effects of pyrostriction and converse piezoelectric effect.

Significance

The developed model can accurately capture the two-way coupling in the analysis of smart composites with segmented and distributed piezoelectric sensors/actuators. It is also capable of providing accurate descriptions on stress, temperature and electric field distributions through the structural thickness for both composite laminate and the piezoelectric devices. The implementation of thermo-piezoelectric-mechanical theory makes the model applicable to address the multifield analysis under various kind of loading, mechanical, thermal and electrical. The developed model is able to render the accurate evaluation of control authority which is mispredicted using the conventional one-way coupling model. Thus, the use of the developed model shows great advantages in the analysis of smart structures with piezoelectric materials.

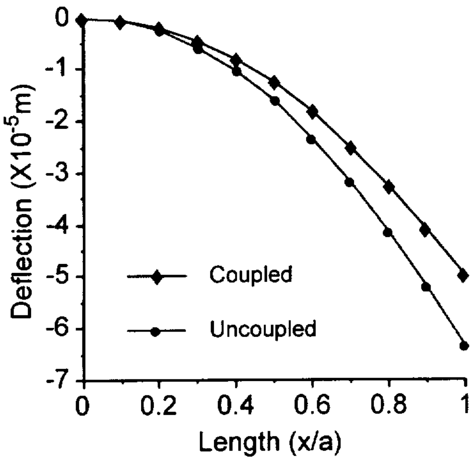

Figure 1 Deflections along plate length with piezoelectric actuation, coupled model and uncoupled model.

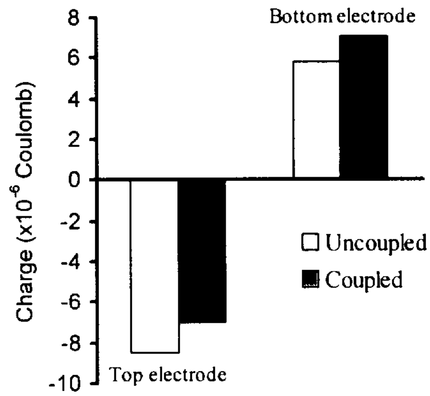

Figure 2 Electric charge of top actuator, coupled model and uncoupled model.

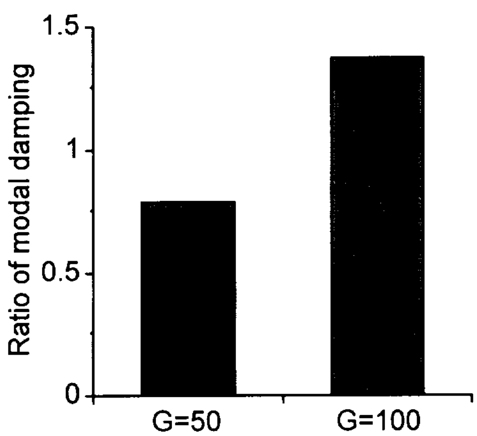

Figure 3 Comparison of modal damping ratio with control, coupled model to uncoupled model.

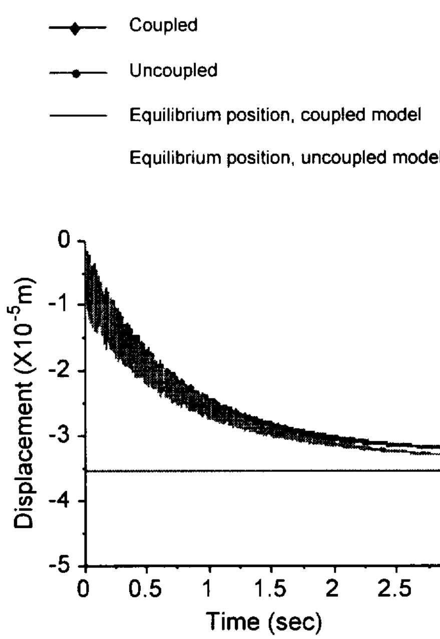

Figure 4 Dynamic tip responses with step surface heat flux, coupled model and uncoupled model.