DYNAMIC ANALYSIS OF COUPLED PIEZOTHERMOELASTIC COMPOSITE PLATE USING FIRST-ORDER SHEAR DEFORMATION THEORY

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ABSTRACT

The present paper deals with the coupling that exists between the piezoelectric and thermal fields in piezoelectric materials. Control of the ensuing responses can be accomplished by applying appropriate electric fields. Thus, by integrating piezoelectric and structural materials, the possibility exists of forming high-strength, high-stiffness structures capable of self-monitoring and self-control. Consequently, in this paper equations governing the linear response of piezothermoelastic media are outlined based on Hamilton's principle and finite element methods with linear shape functions for a first-order shear deformation theory of laminated plates. The method is developed and implemented by time marching method. Analytic results are obtained for a plate simply supported along all edges. Numerical results are presented for cases of a prescribed thermal loading and the conventional active negative control piezoelectric analysis. Additional numerical studies demonstrate effectiveness of thermal environment, as well as the active compensation of these thermal deformation using piezoelectric structures. It is found that the displacements caused by the temperature effects are important in the precision sensing and control of distributed systems by piezoelectric materials.

KEY WORDS: piezothermoelasticity, thermal field, sensor, actuator, negative velocity control,

1 Introduction

The piezoelectric materials are used by researchers in the sensing and control of such distributed systems as beams, plates, and shells. The theory of piezoelectricity with inclusion of thermal field, piezothermoelectricity, is well established in the literature. Among the investigations in piezothermoelasticity, Sunar and Rao [1] presented the use of piezothermoelectricity in the sensing and control of strutural systems using finite element solution to investigate the temperature effects in the sensing and control. Tzou [2] derived the nonlinear piezothermoelastic characteristics and temperature effects of piezoelectric shell laminated systems. Lee and Saravanos [3] extended discrete layer mechanics incorporating the thermal effects to account for the complete coupled mechanical, electrical, and thermal response of piezoelectric composite beams. Tauchert [4] presented a general solution procedure based upon potential functions for the analysis of transversely isotropic thermoelastic and piezothermoelastic bodies. The method is used to derive exact solutions to problems involving the response of a composite circular plate consisting of a piezoelectric material attached to a layer of structural material. Noda [5] presented the dynamic behavior of piezothermoelastic composite plate taking into account the effect of transverse shear theory. He has presented an analytical model of cross-ply laminate and piezoelectric plate subjected to heat, transverse load, and electric field with its edges simply-supported. Ashida and Tauchert [6] solved an inverse transient thermoelastic problem to determine the unknown transient heating temperature distribution on the bottom surface of the disk, when the electric potential distribution on the top surface is given. Aldraihem and Khdeir [7] developed a formulation of analytical models and exact solutions for beams with considering thickness shear and extension piezoelectric actuators. The models are based on the first-order and higher-order beam theories and are solved using the state-space approach along with the Jordan cancnical form. Jonnalagadda and Tauchert [8] used first-order shear deformation theory for the response of piezothermoelastic composite plate subjected to mechanical, thermal, and electric field loadings, where various length-to-depth and aspect ratios are considered. Lam and Reddy [9] developed a finite element model based on the classical laminated plate theory for the active vibration control of a composite plate containing distributed piezoelectric sensors and actuator.

2 Governing Equations

2.1 First-Order Shear Deformation Theory for Laminated Plate

Consistent with the first-order shear deformation theory, the displacement components are taken to be of the form

$$u = u_0 + z\psi_1 \quad , \quad v = v_0 + z\psi_2 \quad , \quad w = w_0 \tag{1}$$

Using the displacement of Eqs. (1), the strains are given by

$$\begin{aligned}
\epsilon_{xx} &= u_{0,x} + z\psi_{1,x} = \epsilon_{xx}^{(0)} + z\epsilon_{xx}^{(1)} \\
\epsilon_{yy} &= v_{0,y} + z\psi_{2,y} = \epsilon_{yy}^{(0)} + z\epsilon_{yy}^{(1)} \\
\epsilon_{zz} &= 0 \\
\epsilon_{yz} &= \frac{1}{2}\left(w_{0,y} + \psi_2\right) \\
\epsilon_{xz} &= \frac{1}{2}\left(w_{0,x} + \psi_1\right) \\
\epsilon_{xy} &= \frac{1}{2}\left(u_{0,y} + z\psi_{1,y} + v_{0,x} + z\psi_{2,x}\right) = \epsilon_{xy}^{(0)} + z\epsilon_{xy}^{(1)}
\end{aligned} \tag{2}$$

The N-layered of the piezothermoelastic laminate exhibits symmetry for the material constants with respect to principal $X1$, $X2$ and $X3$ axes. The constitutive equations for a typical layer k, referenced to an arbitrary plate coordinate axes X, Y, and $Z = X3$, are

$$\begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{pmatrix} = \begin{pmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 & 0 & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 & 0 & \bar{Q}_{26} \\ 0 & 0 & \bar{Q}_{44} & \bar{Q}_{45} & 0 \\ 0 & 0 & \bar{Q}_{45} & \bar{Q}_{55} & 0 \\ \bar{Q}_{16} & \bar{Q}_{26} & 0 & 0 & \bar{Q}_{66} \end{pmatrix} \left(\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{yz} \\ \epsilon_{xz} \\ \epsilon_{xy} \end{pmatrix} - \begin{pmatrix} \bar{\alpha}_1 \\ \bar{\alpha}_2 \\ \bar{\alpha}_4 \\ \bar{\alpha}_5 \\ \bar{\alpha}_6 \end{pmatrix} \theta \right) - \begin{pmatrix} 0 & 0 & \bar{e}_{31} \\ 0 & 0 & \bar{e}_{32} \\ \bar{e}_{14} & \bar{e}_{24} & 0 \\ \bar{e}_{15} & \bar{e}_{25} & 0 \\ 0 & 0 & \bar{e}_{36} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} \tag{3}$$

Integrating the constitutive relations of Eqs. (3) through the composite plate thickness leads to the structure material stiffness relationships. The force and moment resultants are related to the strains using the definition of forces and moments and the constitutive relations (2) as

$$\begin{aligned}
\begin{pmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{pmatrix} &= \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{pmatrix} dz \\
&= \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} \{ \begin{pmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{pmatrix}^{(k)} \left(\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \end{pmatrix} - \begin{pmatrix} \bar{\alpha}_1 \\ \bar{\alpha}_2 \\ \bar{\alpha}_6 \end{pmatrix}^{(k)} \theta \right) - \begin{pmatrix} \bar{e}_{31} \\ \bar{e}_{32} \\ \bar{e}_{36} \end{pmatrix}^{(k)} E_z^{(k)} \} \\
&= \begin{pmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{pmatrix} \begin{pmatrix} \epsilon_{xx}^{(0)} \\ \epsilon_{yy}^{(0)} \\ \epsilon_{xy}^{(0)} \end{pmatrix} + \begin{pmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{pmatrix} \begin{pmatrix} \epsilon_{xx}^{(1)} \\ \epsilon_{yy}^{(1)} \\ \epsilon_{xy}^{(1)} \end{pmatrix} - \begin{pmatrix} N_{xx}^{\theta} \\ N_{yy}^{\theta} \\ N_{xy}^{\theta} \end{pmatrix} - \begin{pmatrix} N_{xx}^{E} \\ N_{yy}^{E} \\ N_{xy}^{E} \end{pmatrix}
\end{aligned} \tag{4}$$

Similarly, we have

$$\begin{pmatrix} M_{xx} \\ M_{yy} \\ M_{xy} \end{pmatrix} = \begin{pmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{pmatrix} \begin{pmatrix} \epsilon_{xx}^{(0)} \\ \epsilon_{yy}^{(0)} \\ \epsilon_{xy}^{(0)} \end{pmatrix} + \begin{pmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{pmatrix} \begin{pmatrix} \epsilon_{xx}^{(1)} \\ \epsilon_{yy}^{(1)} \\ \epsilon_{xy}^{(1)} \end{pmatrix} - \begin{pmatrix} M_{xx}^{\theta} \\ M_{yy}^{\theta} \\ M_{xy}^{\theta} \end{pmatrix} - \begin{pmatrix} M_{xx}^{E} \\ M_{yy}^{E} \\ M_{xy}^{E} \end{pmatrix} \tag{5}$$

And

$$\begin{aligned}
\begin{pmatrix} Q_y \\ Q_x \end{pmatrix} &= \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} \begin{pmatrix} \sigma_{yz} \\ \sigma_{xz} \end{pmatrix} dz \\
&= \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} \{ \begin{pmatrix} \bar{Q}_{44} & \bar{Q}_{45} \\ \bar{Q}_{45} & \bar{Q}_{55} \end{pmatrix}^{(k)} \left(\begin{pmatrix} \epsilon_{yz} \\ \epsilon_{xz} \end{pmatrix} - \begin{pmatrix} \bar{\alpha}_4 \\ \bar{\alpha}_5 \end{pmatrix}^{(k)} \theta \right) - \begin{pmatrix} \bar{e}_{14} & \bar{e}_{24} \\ \bar{e}_{15} & \bar{e}_{25} \end{pmatrix}^{(k)} \begin{pmatrix} E_x \\ E_y \end{pmatrix} \} \\
&= \begin{pmatrix} A_{44} & A_{45} \\ A_{45} & A_{55} \end{pmatrix} \begin{pmatrix} \epsilon_{yz} \\ \epsilon_{xz} \end{pmatrix} - \begin{pmatrix} Q_y^{\theta} \\ Q_x^{\theta} \end{pmatrix} - \begin{pmatrix} Q_y^{E} \\ Q_x^{E} \end{pmatrix}
\end{aligned} \tag{6}$$

where $\{N^\theta\}$, $\{Q^\theta\}$, and $\{M_\theta\}$ are thermal force and moment resultants and are defined as

$$\begin{pmatrix} N^\theta_{xx} & , M^\theta_{xx} \\ N^\theta_{yy} & , M^\theta_{yy} \\ N^\theta_{xy} & , M^\theta_{xy} \end{pmatrix} = \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} \begin{pmatrix} \bar\lambda_1 \\ \bar\lambda_2 \\ \bar\lambda_6 \end{pmatrix}^{(k)} \theta(1,Z)dZ$$

$$\begin{pmatrix} Q^\theta_y \\ Q^\theta_x \end{pmatrix} = \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} \begin{pmatrix} \bar\lambda_4 \\ \bar\lambda_5 \end{pmatrix}^{(k)} \theta dZ \tag{7}$$

Also, $\{N^E\}$, $\{Q^E\}$, and $\{M^E\}$ are the electric force and moment resultants and are defined as

$$\begin{pmatrix} N^E_{xx} & , M^E_{xx} \\ N^E_{yy} & , M^E_{yy} \\ N^E_{xy} & , M^E_{xy} \end{pmatrix} = \sum_{k=1}^{N_a} \int_{Z_k}^{Z_{k+1}} \begin{pmatrix} \bar e_{31} \\ \bar e_{32} \\ \bar e_{36} \end{pmatrix} E_z(1,Z)dZ$$

$$\begin{pmatrix} Q^E_y \\ Q^E_x \end{pmatrix} = \sum_{k=1}^{N_a} \int_{Z_k}^{Z_{k+1}} \begin{pmatrix} \bar e_{14} & \bar e_{24} \\ \bar e_{15} & \bar e_{25} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} \tag{8}$$

The in-plane and bending composite plate stiffnesses are given as

$$\{A_{ij}, B_{ij}, D_{ij}\} = \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} (\bar Q_{ij})^{(k)} (1, Z, Z^2) dZ$$

$$= \sum_{k=1}^{N} ((Z_{k+1} - Z_k), \frac{1}{2}(Z^2_{k+1} - Z^2_k), \frac{1}{3}(Z^3_{k+1} - Z^3_k)) \qquad i,j = 1,2 \ \ and \ \ 6 \tag{9}$$

The composite plate shear stiffness coefficient S_{ij} is given by

$$S_{ij} = \sum_{k=1}^{N} \int_{Z_k}^{Z_{k+1}} k_p k_q (\bar Q_{ij})^{(k)} dZ = \sum_{k=1}^{N} k_p k_q (\bar Q_{ij})^{(k)} (Z_{k+1} - Z_k) \qquad p = 6-i \ , \ q = 6-j \ , \ \ i,j = 4,5 \tag{10}$$

The equations of motion of a laminated composite plate can be derived using the Hamilton's principle as

$$\int_0^t (\delta U + \delta V - \delta K) dt = 0 \tag{11}$$

where δU, δV, and δK are the virtual strain energy, virtual work done by external forces, and virtual kinetic energy, respectively. Using Eqs. (11) in elastic body with stresses and srtains from Eqs. (1) to (6), we obtain the governing equations of motion with appropriate boundary conditions as

$$\begin{aligned} \delta u_0 : &\quad N_{xx,x} + N_{xy,y} = I_0 \ddot u_0 + I_1 \ddot\psi_1 \\ \delta v_0 : &\quad N_{xy,x} + N_{yy,y} = I_0 \ddot v_0 + I_1 \ddot\psi_2 \\ \delta w_0 : &\quad Q_{x,x} + Q_{y,y} + q = I_0 \ddot w_0 \\ \delta \psi_1 : &\quad M_{xx,x} + M_{xy,y} - Q_x = I_1 \ddot u_0 + I_2 \ddot\psi_1 \\ \delta \psi_2 : &\quad M_{xy,x} + M_{yy,y} - Q_y = I_1 \ddot v_0 + I_2 \ddot\psi_2 \end{aligned} \tag{12}$$

2.2 Sensor and Actuator Equations

The electromechanical coupling is a two-way coupling. The effect of applied electrical field on stresses is, as indicated by Eqs. (3), is analogous to the effect of the temperature field. The components D_i of electrical displacement vector are related to the components of strains and electrical field by the following relation

$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & \bar e_{14} & \bar e_{24} & 0 \\ 0 & 0 & \bar e_{15} & \bar e_{25} & 0 \\ \bar e_{31} & \bar e_{32} & 0 & 0 & \bar e_{36} \end{pmatrix} \begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{yz} \\ \epsilon_{xz} \\ \epsilon_{xy} \end{pmatrix} - \begin{pmatrix} \bar\varepsilon_{11} & \bar\varepsilon_{12} & 0 \\ \bar\varepsilon_{12} & \bar\varepsilon_{22} & 0 \\ 0 & 0 & \bar\varepsilon_{33} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} \tag{13}$$

This electromechanical equation provides the starting point for the derivation of the sensor and actuator equations. According to the Gauss law, the closed circuit charge measured through the electrodes of the k-th layer is

$$Q_{is}^k = \frac{1}{2}\int_{SI} D_i ds_i + \frac{1}{2}\int_{SI} D_i ds_i \qquad i = X, Y, Z \tag{14}$$

where $SI = S_b \bigcap S_t$ is the intersection of the electrode surfaces on each of the both sides of the lamina. When Eq. (13) is applied to sensors where the converse piezoelectric effect is negligible and the external applied charge is zero, the sensed charge can be calculated from Eq. (13) and the total charge in the laminate is calculated by summing over the number of sensor layers as

$$Q_{is}^k = \frac{1}{2}\sum_{k=1}^{N_s}(\int_{SI} D_i ds_i + \int_{SI} D_i ds_i) \tag{15}$$

By substituting Eq. (13) into Eq. (15), we obtain the closed-circuit charge sensor equation in each direction which relates the output signal to the plate deformation. The current $I_i(t)$ on each surface of the sensor is given by

$$I_i(t) = \frac{dQ_{is}}{dt} \tag{16}$$

When the sensors are used as strain rate tensors, the current can be converted to the open circuit sensor voltage output V_s as

$$V_{is}(t) = G_s I_i(t) = G_s \frac{dQ_{is}}{dt} \tag{17}$$

where G_s is the gain of the current amplifier, which transforms the sensor current to voltage. The actuator equations for piezoelectric actuator can be derived using the induced strain actuation. The distributed sensor generates a voltage when the structure is oscillating. Thus the sensor forces and moments are evaluated using

$$E_s = \{\frac{V_{xs}}{a}\ \frac{V_{ys}}{b}\ \frac{V_{zs}}{h_s}\}^T \tag{18}$$

This signal is fed back into the distributed actuator using a control algorithm, as shown in Fig. (1). The actuating voltage V_a under a constant gain control algorithm can be expressed as

$$V_{ia}(t) = G_a V_{is} = G_a G_s \frac{dQ_{is}}{dt} = G \frac{dQ_{is}}{dt} \tag{19}$$

where G_a is the gain to provide feedback control and G is the total gain of system. The actuating forces $\{N_E\}$, $\{Q_E\}$, and moments $\{M_E\}$ are determined in terms of the strain rate in the sensor layer from Eq. (8).

3 Finite Element Formulation

For the finite element approximation of the piezothermoelastic equation, the shape functions for the displacement components are assumed as

$$\begin{aligned} u_{el} &= N_u u_i \quad , \quad v_{el} = N_u v_i \quad , \quad w_{el} = N_u w_i \\ \psi_{1el} &= N_u \psi_{1i} \quad , \quad \psi_{2el} = N_u \psi_{2i} \end{aligned} \tag{20}$$

Applying the Galerkin method to Eqs. (12) with the shape functions of Eqs. (20), using Eqs. (3) to (10), and for the active compensation Eqs. (13) to (19), the finite element dynamic matrix equation is obtained as

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} + \{F_\theta\} \tag{21}$$

As shown in Eq. (21), the voltage control algorithm given by Eq. (19) has a damping effect on the vibration suppression for a distributed system. This equation can be used to study the temperature effects in a distributed control systems with piezothermoelectric sensors and actuators. The temperature effects may be important if the control system has to operate in an environment where thermal field is considered. It is found that the displacements caused by the temperature effects are important in the precision sensing and control of distributed systems by the piezothermoelectric materials.

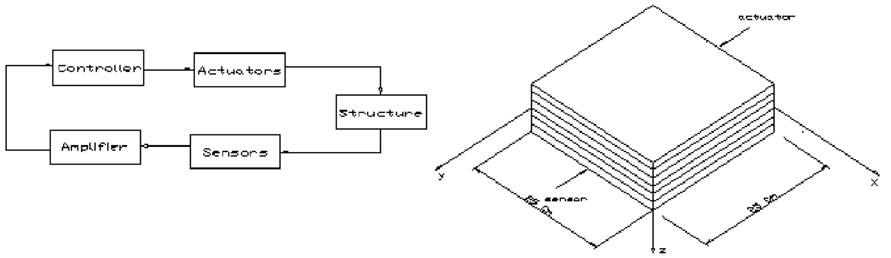

Figure 1: A laminated composite plate with integrated piezoelectric sensors and actuators

4 Sample Problems

In order to verify the effectiveness of thermal environment on smart structure, a simply supported thick laminated composite plate ($25cm \times 25cm$) with both the upper and lower surfaces symmetrically bonded by piezothermoelectric material, as shown in Fig. (1), is studied. The plate consists of four composite layers and two outer piezo-layers. The stacking sequence of the composite plate is cross-ply $(0/90)_s$. The total thickness is $5.25cm$ and each piezo-layer is $0.13cm$. The adhesive layers are neglected. The plate is made of an aluminum layer and two layers of piezoelectric films made of polyvinylidene fluoride (PVDF) [1]. Plate thickness is represented by h, and the plate dimensions are represented by a and b along the X and Y axes, respectively. Shear correction factors of $k_1 = k_2 = 0.91287$ are used throughout. Temperature loading for the composite plate is a linear thermal loading of the form

$$\theta(z) = \frac{\theta_0 + \theta_N}{2} + \frac{z(\theta_0 - \theta_N)}{h} \tag{22}$$

In which θ_0 and θ_N are the temperature increases at the lower and upper plate surfaces, respectively. Uniform surface mechanical loading is $F = 500N/m^2$. For all deflection results, $\bar{w}$ is the nondimensionalized center transverse deflection of the plate. The plate has simply supported boundary condition in all edges as

$$\begin{aligned} X = 0, a \quad &; \qquad v_0 = w = \psi_2 = N_{xx} = M_{xx} = 0 \\ Y = 0, b \quad &; \qquad u_0 = w = \psi_1 = N_{yy} = M_{yy} = 0 \end{aligned} \tag{23}$$

The finite element method, using time marching approach by the Newmark direct integration method, is used to obtain the solution. To introduce temperature effects, it is assumed that the bottom surface of the composite plate is heated and cooled. Temperature values are $\theta_0 = 300^{(ok)}$ (no thermal loading) and $\theta_N = 400^{(ok)}$ or $\theta_N = 200^{(ok)}$. The side boundary of the plate is taken to be thermally insulated. It is assumed that the center of simply supported plate is vibrating freely due to an initial surface mechanical loading. The importance of temperature effects in the free vibration of plate, when temperature is increasing and decreasing, are shown in Fig. (2). The increase of the temperature cause the increase of the vibration amplitude. When the temperature is decreased, the vibration amplitude is decreased.

The same structure is considered again to investigate the active vibration control of the composite plate under the integrated sensors and actuators. In vibration control, the lower piezoelectric layer is served as sensor and the upper one as the actuator. In the present work, a negative velocity active feedback control algorithm is used. Figure (3) shows the suppression of the free vibration of the plate under the distributed piezoelectric sensor and actuator. Because of damping matrix in Eq. (21), the increase of feedback control gains result in a higher damping matrix in the system equation. Consequently, the vibration of the plate is suppressed much faster at higher feedback control gains.

Now, dynamic case studies are carried out to observe the temperature effects in the piezoelectric control systems. When the distributed system is subjected to the same thermal field, as in the previous cases, the response of the closed-loop control system is different as shown in Fig. (4) and Fig. (5). The increasing of thermal field has introduced additional deflection in the closed-loop control system, which is important to observe for the precision sensing and control. It also appears that decreasing of thermal field has slightly slower deflection. This numerical results also show the importance of adding the temperature effects in the precision distributed control of systems and hence it has the advantages of being an accurate model for the control cases.

It is also seen that the vibrations are damped out more quickly when higher feedback control gains, even with existing thermal field, are used. However, it must be noted that the gains should be limited for the sake of the breakdown voltage of the piezoelectric having thermal fields.

5 Conclusions

The importance of plate thickness on the response of piezothermoelastic composite plate has been illustrated using the first-order shear deformation theory. The governing equations are obtained using the Hamilton's principle and the finite element method is employed to obtain the solution by the Newmark time marching method. The numerical results are presented for the free vibration of the plate under the influence of thermal fields. Also, the negative velocity feedback control algorithm is used in a closed control loop to couple the direct and converse piezoelectric effects as a distributed system. Then, dynamic case studies are carried out to observe the temperature effects in the piezoelectric control systems. The piezothermoelastic equations are used for sensors and actuators, which show the importance of adding the temperature effects in the precision of distributed control systems.

Nomenclature

$[C]$	damping matrix
$\bar{e}_{ij}$	transformed piezoelectric coefficient
$\{E\}$	electric field vector
$\{F\}$	external mechanical force vector
$\{F_\theta\}$	thermal force vector
$[K]$	element matrix
$[M]$	mass matrix
N_a	number of actuating layer
N_s	number of sensor layer
N_u	bilinear shape function matrix
q	applied surface uniform mechanical loading
$\bar{Q}_{ij}$	transformed plane-stress reduced elastic stiffness coefficient
$\{u\}$	nodal displacement vector
u_0	middle surface displacement in X direction
v_0	middle surface displacement in Y direction
w_0	middle surface displacement in Z direction
ψ_1	rotation about the X axis
ψ_2	rotation about the Y axis
θ	temperature rise from the stress-free reference temperature
$\bar{\alpha}_i$	transformed thermal expansion coefficient
$\bar{\lambda}$	transformed stress-temperature coefficient
$\bar{\varepsilon}_{ij}$	transformed electric permittivity

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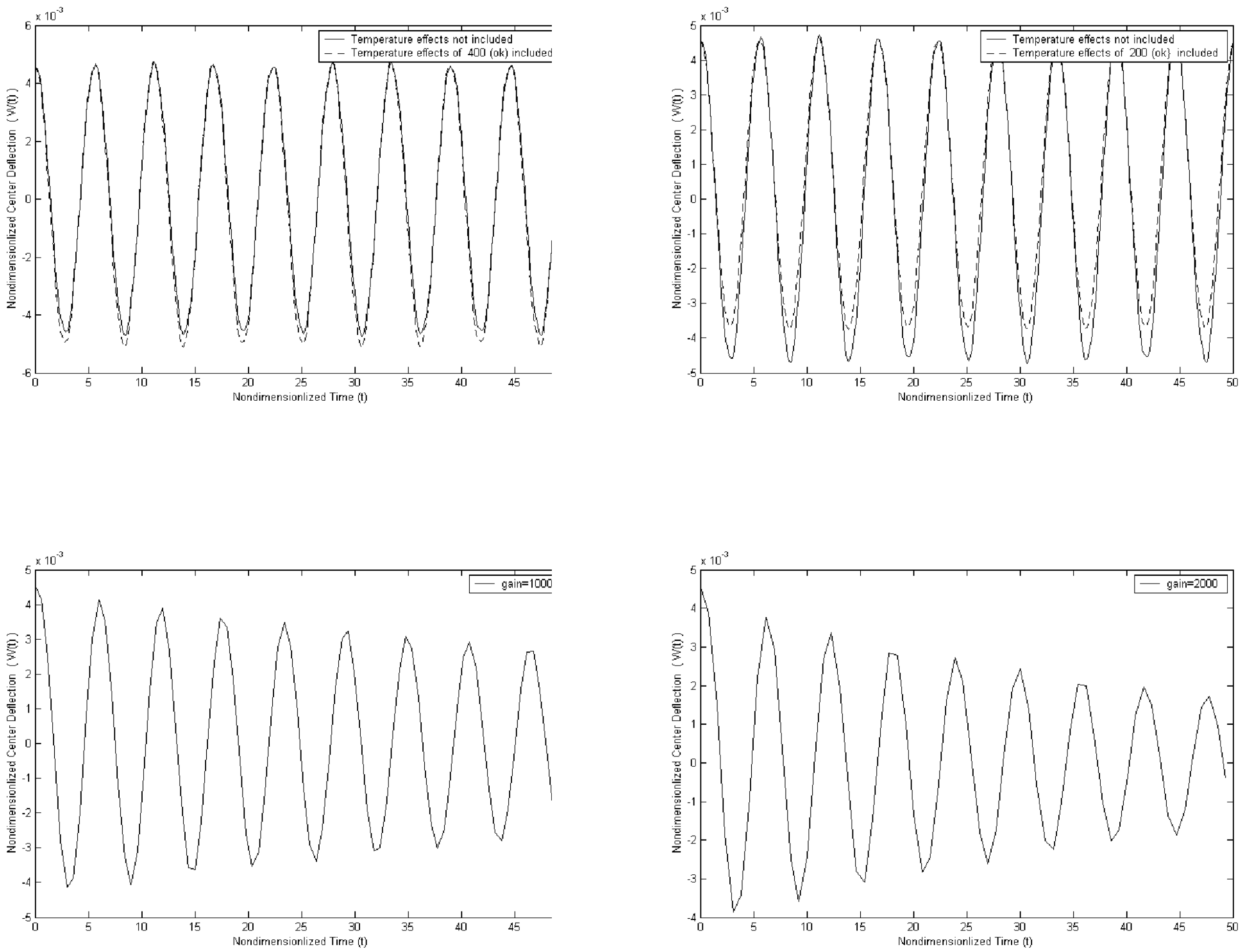

Figure 3: The effect of feedback control gain on the transient response of center transverse deflection ($\bar{w}$).

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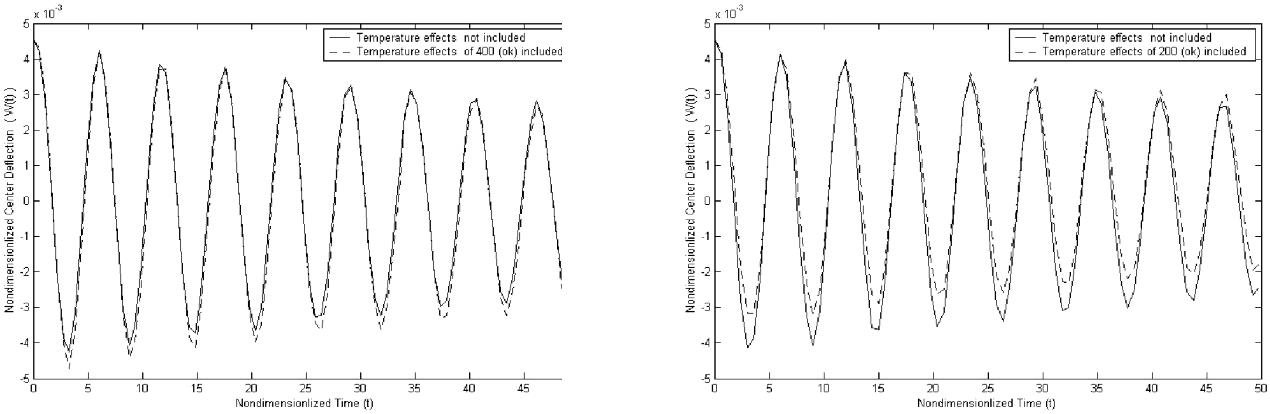

Figure 4: The effect of feedback control gain $G = 1000$ on the transient response of center transverse deflection ($\bar{w}$) at the temperature condition of $\theta_N = 400^{(ok)}$ and $\theta_N = 200^{(ok)}$

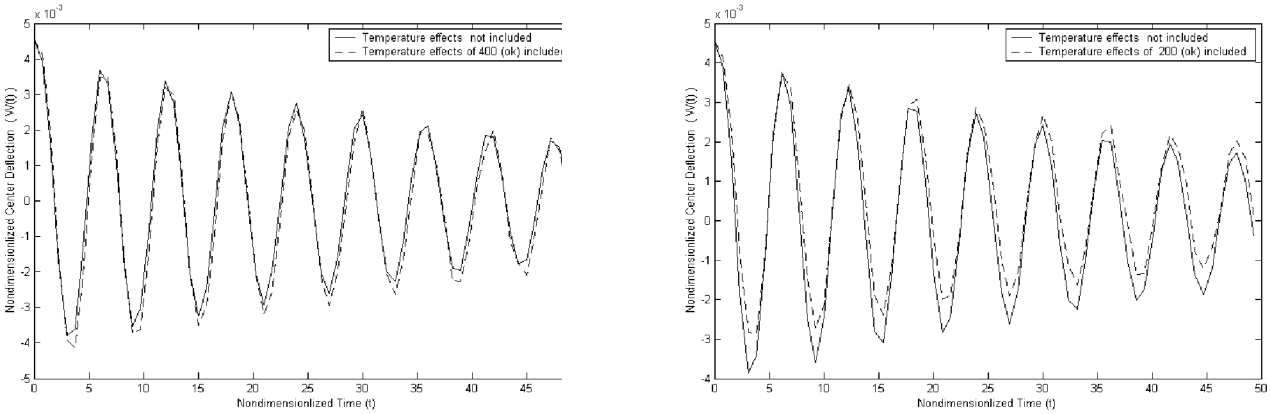

Figure 5: The effect of feedback control gain $G = 2000$ on the transient response of center transverse deflection ($\bar{w}$) at the temperature condition of $\theta_N = 400^{(ok)}$ and $\theta_N = 200^{(ok)}$