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Vibration suppression of laminated plates with 1–3 piezoelectric fiber-reinforced composite layers equipped with interdigitated electrodes

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Abstract

Piezoelectric fiber-reinforced composites offer a great potential for applications in the vibration control of flexible structures. This paper presents an analytical formulation for structural vibration control of laminated plates consisting of 1–3 piezoelectric fiber-reinforced composite layers and orthotropic composite layers. The active control electric field is applied to the piezocomposite layers equipped with Interdigitated Electrodes (IDE). Based on the thin plate theory, the governing differential equations for axial vibration and transverse vibration are established, and the solution is obtained through the separation of variables and Fourier expansion methods. A numerical example analysis is carried out to investigate the dynamic characteristics of the laminated plates. Results show that the vibration suppression can be achieved by adopting a time-dependent control voltage. The axial vibration response along y-direction requires more time to damp out than that for x-direction due to the anisotropic properties of the laminated plates. Results presented here can be used to enhance the understanding of the static and dynamic response behavior of the 1–3 piezoelectric composite structures.

Keywords: Laminated plates; Analytical model; 1–3 Piezoelectric composites

1. Introduction

Piezoelectric fiber-reinforced composite actuators have received considerable attention [1–3] due to their higher potential applicability for the vibration control in various industrial and research areas. The materials, incorporated with conventional structures, can generate control forces to structural elements according to the applied voltage. Conversely, they can be used as sensing elements due to the direct piezoelectric effect. Furthermore, this kind of composites has the ability to create anisotropic laminate layers, which makes them particularly useful in applications requiring off-axis or twisting motions. The conventional way to lay electrodes for 1–3 piezocomposite laminated plates is depositing them on the top and bottom surfaces of the matrix, and thus the electric field is yielded along the thickness direction. Therefore, for this plate system, the effective piezoelectric constant of piezocomposite layers, e_{31}, plays an important role on the active control of the vibration. As known, the piezoelectric constant e_{31} is generally less than e_{33} for the piezoelectric materials. In order to create the larger strain in the piezoelectric fiber direction, an interdigitated electrode, i.e. IDE, was proposed by Hagood et al. [4–6] (see Fig. 1). With interdigitated electrodes, the piezoelectric fibers in piezocomposite layer are poled along the fiber direction, causing an anisotropy piezoelectric deformation, and thus the effective constant of piezocomposite, e_{33}, will play an important dominant role on the active control.

A pioneering work is Alik and Hughes [7] who analyzed the interactions between electricity and elasticity by developing a tetrahedral finite element. Shape control and dynamic control of the referred "intelligent structures" described by Crawley and de Luis [8]. Several researchers have carried out the modeling of composites structures containing piezolaminated sensors and actuators using the finite element formulation. Liu et al. [9] developed a finite element formulation to model the dynamic and static

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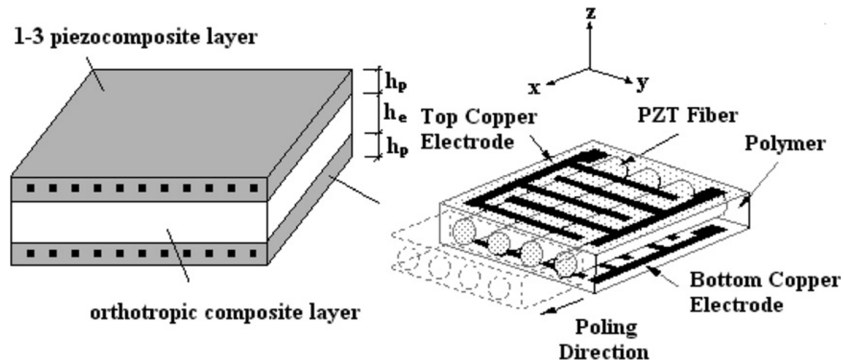

Fig. 1. A rectangular composite laminate with 1–3 piezoelectric composite layers.

response of laminated composite plates containing piezoelectric sensors and actuators subjected to both mechanical and electrical loadings. Reddy [10] presented a detailed theoretical formulation, the Navier solution and finite element models based on the classical and shear deformation plate theories, for the analysis of laminated composite plates with integrated sensors and actuators. Lee and Han [11,12] extended the layerwise displacement theory [13] to analyzed composite plates with distributed piezoelectric actuators using a refined finite element method.

Many investigators have also developed several analytical models for the dynamic control of laminated plates with piezoelectric ceramic sensors and actuators. Using the first-order shear deformation, Bohua and Huang [14] derived an analytical formulation for modeling the behavior of laminated composite plates with integrated piezoelectric sensor and actuator. An axisymmetric shell model was developed by Correia et al. [15], which combines the equivalent single-layer higher order shear deformation theory to represent the mechanical behavior with a layerwise discretization in the thickness direction to represent the distribution of the electrical potential. Birman [16], using an analytical method, studied the problem of actively controlling the transient vibrations of a plate reinforced with piezoceramics stiffener-actuators. An exact three-dimensional solution was obtained by Baillargeon and Vel [17], using the power series method, for the cylindrical bending vibration of simply supported laminated composite plates with an embedded piezoelectric shear actuator.

However, most previous works gave much attention to model the dynamic behavior of laminated plates with piezoelectric ceramic layers. So far, the work reported in the area of laminated plate with 1–3 piezocomposite layers is still quite limited, especially for active vibration control of laminates with 1–3 piezoelectric fiber reinforced composite layer equipped with the IDE. Ping et al. [18] presented a one dimensional piezoelectric mass-dashpot spring parallel model for active piezoelectric fiber-reinforced viscoelastic materials, and only the dynamic characteristics of a one dimensional beam system with active piezoelectric fiber reinforced viscoelastic composite damping layers is investigated.

Therefore, it is the aim of the present study to develop an three dimensional analytical model for active control of laminated plates with active 1–3 piezoelectric fiber reinforced composite damping layers. The control voltage, applied to the 1–3 piezocomposite layers with the Interdigitated Electrodes, would induce the electric fields in the fiber direction. Firstly, the governing equations for axial vibration response and transverse vibration response of the laminated plates are established based on the thin plate theory. Secondly, the derived governing differential equations are decoupled by using the separation of variables and Fourier expansion methods. Negative velocity feedback control is considered, and Newmark method is used to obtain the dynamic response of the laminated structures. The numerical analysis is conducted to investigate the dynamic characteristics of a three-layer laminates with two 1–3 piezocomposite damping layers. The results obtained can be used not only to assess various approximate theories, but also enhance the understanding of the static and dynamic behavior of 1–3 piezoelectric fiber-reinforced composite structures.

2. Formulations for in-plane axial vibration of the plate

The rectangular laminated plate considered here consists of an orthotropic graphite/epoxy composite layer sandwiched between two 1–3 fiber-reinforced piezoelectric composite layers, illustrated in Fig. 1. A control voltage is applied to the 1–3 piezocomposite layers equipped with the IDE, which induces electric field along the piezoelectric fiber direction, i.e. x-direction. a and b are the side lengths in the x and y directions, and h is the total thickness of the plate. The origin of the z coordinate is at the center of the orthotropic composite layer.

According to the thin plate theory, the displacements of the laminates are

$$u(x,y,z,t) = u_0(x,y,t) - z\frac{\partial w}{\partial x} \tag{1a}$$

$$v(x,y,z,t) = v_0(x,y,t) - z\frac{\partial w}{\partial y} \tag{1b}$$

$$w(x,y,z,t) = w(x,y,z,t) \tag{1c}$$