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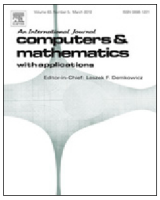

Free vibration of functionally graded carbon nanotube reinforced composite plates integrated with piezoelectric layers

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ABSTRACT

In the present research, free vibration behavior of carbon nanotube reinforced composite (CNTRC) plates integrated with piezoelectric layers at the bottom and top surfaces is analyzed. Plate is modeled according to the first order shear deformation plate theory. Distribution of CNTs across the plate thickness may be functionally graded (FG) or uniformly distributed (UD). Properties of the composite media are obtained according to a modified rule of mixtures approach which contains efficiency parameters. Distribution of electric potential across the piezoelectric thickness is assumed to be linear. The complete set of motion and Maxwell equations of the system are obtained according to the Ritz formulation suitable for arbitrary in-plane and out-of-plane boundary conditions. Besides, two types of electrical boundary conditions, namely, closed circuit and open circuit are considered for the free surfaces of the piezoelectric layers. Chebyshev polynomials are used as the basis functions in Ritz approximation. The resultant eigenvalue system is solved to obtain the frequencies of the system as well as the mode shapes. It is shown that, fundamental frequency of a closed circuit plate is always higher than a plate with open circuit boundary conditions.

1. Introduction

Due to their electromechanical coupling, piezoelectric materials have wide range of applications. Various researches are available on the analysis of plates and shells integrated with piezoelectric layers. These materials as a branch of smart materials are used extensively to suppress the forced vibration [1–6], control the free vibration [7–12], decrease the deflection and stresses [13–15], delay the buckling [16–20], decrease the post-buckling deflection [17–20], flutter control [21] and suppress the snap-through phenomenon [22,23].

Carbon nanotubes (CNTs) are known as a branch of novel materials with fascinating mechanical, thermal and electrical properties. As a result, CNTs are known as a promising candidate for reinforcement of composites [24]. As reported by Kwon et al. [25] rather than the uniform distribution of CNTs in a matrix, linear distribution of CNTs in a matrix may be achieved using the power metallurgy fabrication process. Consequently, a novel class of materials titled functionally graded carbon nanotube reinforced composites (FG-CNTRC) have shown increasing attention in the past years. The fundamental research on FG-CNTRC belongs to Shen [26]. Shen [26] studied the nonlinear bending response of an FG-CNTRC rectangular plate. Shen revealed that bending moment acting on the plate may be decreased significantly upon introduction of functionally graded distribution of CNTs. Following this research, a large number of investigations are devoted to FG-CNTRC beams, plates and

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shells of various shapes. In the next paragraphs, some of the major works dealing with vibration of FG-CNT plates, major researches on other structural responses of FG-CNT plates, and behavior of FG-CNT structures integrated with piezoelectric layers are provided.

A state space approach is proposed by Zhang et al. [27] to study the free vibration characteristics of rectangular Lévy plates where two opposite edges of the plate are simply supported. Zhang et al. [28] and lei et al. [29] studies, respectively, the free vibration characteristics of FG-CNTRC plates with elastically restrained edges and laminated plates with FG-CNTRC layers. Zhu et al. [30] investigated the free vibration and static response of FG-CNTRC plates using finite elements method [30]. Zhang et al. investigated the free vibration characteristics of FG-CNTRC skew plates [31], triangular plates [32] and cylindrical panels [33] using element free methods. In these researches, it is shown that, natural frequencies of plates and panels are affected by distribution and volume fraction of CNTs. Malekzadeh and Zarei [34] examined the free vibration characteristics of laminated plates containing FG-CNTRC layers in an arbitrary straight-sided quadrilateral shape. Malekzadeh and Heydarpour [35] investigated the free vibration and static response of laminated plates with FG-CNTRC layers using a mixed Navier-layerwise differential quadrature method. In this research, plates with all edges simply supported are considered. Natarajan et al. [36] applied a higher order shear and normal deformable plate formulation to study the statics and free vibrations of single layer FG-CNTRC plates and also sandwich plates with FG-CNTRC face sheets. Mirzaei and Kiani [37] analyzed the free vibration characteristics of perforated rectangular plates using a Chebyshev Ritz formulation. Kiani [38] also investigated the free vibration of FG-CNTRC rectangular plates located on point supports using the Lagrangian multipliers. In another study, Kiani [39] obtained the free vibration characteristics of FG-CNTRC skew plates. Wang and Shen investigated the geometrically linear and nonlinear free vibrations of single layer FG-CNTRC plates [40] and also sandwich plates with isotropic homogeneous stiff core and FG-CNTRC face sheets [41]. In this analysis interaction of the plate with two parameter elastic foundation is also taken into account.

Similar to linear vibration analysis, buckling of skew FG-CNTRC plates [42], postbuckling of FG-CNTRC plates subjected to in-plane compressive loads [43,44], linear stress analysis of FG-CNTRC plates [45], geometrically nonlinear response of FG-CNTRC skew [46], rectangular [47] (on Pasternak elastic foundation) and quadrilateral plates [48], dynamic stability of cylindrical panels [49], flutter control of FG-CNTRC cylindrical panels [50] and dynamic response of FG-CNTRC rectangular plates [51] are studied by Liew and his co-authors.

On the other hand researches on FG-CNTRC plates integrated with piezoelectric layers are limited in number. Alibeigloo analyzed the elastic [52] and thermoelastic [53] response of arbitrary thick FG-CNTRC plate integrated with sensor and actuator piezoelectric layers based on the three dimensional theory of elasticity. Solution method of this research, however is suitable only for plates simply supported all around. Free vibration, thermal buckling and parametric stability response of moderately thick plates integrated with actuator piezoelectric layers is investigated by Rafiee et al. [54]. In this research initial geometrical imperfection is also included into the formulation. Wu and Chang [55] analyzed the buckling of an arbitrary thick FG-CNTRC plate integrated with piezoelectric layers based on the three dimensional elasticity formulation. Zhang et al. [56] proposed a strategy to active shape control of FG-CNTRC rectangular plates integrated with piezoelectric patches.

As the above literature survey reveals, less attention is devoted to hybrid piezoelectric-FG-CNTRC structures. Especially free vibration of FG-CNTRC plates with arbitrary mechanical and electrical boundary conditions has not been reported yet in the open literature which is the scope of the present research. This investigation deals with free vibration characteristics of FG-CNTRC rectangular plates integrated with piezoelectric layers at the bottom and top. First order shear deformation plate theory is used to estimate the kinematics of the plate. Distribution of electric potential through the thickness of the piezoelectric layers is assumed to be linear. Properties of the host layer of the plate are obtained according to a refined approach based on the rule of mixtures which accounts for efficiency parameters. Two types of electrical boundary conditions, namely, open and closed circuit are considered for the free surfaces of the piezoelectric layers. A Ritz method with Chebyshev polynomials as the basis of the shape functions is implemented to obtain the frequencies and the mode shapes of the hybrid FG-CNTRC plates with arbitrary in-plane and out-of-plane boundary conditions. It is shown that, volume fraction of CNTs, distribution pattern of CNTs, mechanical and electrical boundary conditions and thickness of the smart layers affect the vibration behavior of the plate.

2. Basic formulation

An FG-CNTRC rectangular plate integrated with two perfectly bounded identical piezoelectric layers at the bottom and top surfaces is considered in this research. Thickness, width and length of the host plate are denoted by, h, b and a, respectively. Thickness of the top and bottom piezoelectric layers are also denoted by h^p. The conventional Cartesian coordinate system with its origin located at the center of the plate where $-0.5a \leq x \leq +0.5a$, $-0.5b \leq y \leq +0.5b$, and $-0.5h - h^p \leq z \leq +0.5h + h^p$ is considered.

Host layer is made from a polymeric matrix reinforced with single walled carbon nanotube (SWCNT). Distribution of SWCNT across the plate thickness may be uniform (referred to as UD) or functionally graded (referred to as FG) [31]. In this research, three types of FG distribution of CNTs and the UD case are considered. FG-V, FG-O and FG-X CNTRC are the functionally graded distribution of carbon nanotubes through the thickness direction of the composite rectangular plate. In Table 1 distribution function of CNTs across the plate thickness is provided.

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