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Nonlinear vibration of nanotube-reinforced composite cylindrical panels resting on elastic foundations in thermal environments

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ABSTRACT

This paper investigates the large amplitude vibration behavior of nanocomposite cylindrical panels resting on elastic foundations in thermal environments. Two kinds of carbon nanotube-reinforced composite (CNTRC) panels, namely, uniformly distributed and functionally graded reinforcements, are considered. The material properties of FG-CNTRC panels are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. The motion equations are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The panel-foundation interaction and thermal effects are also included and the material properties of CNTRCs are assumed to be temperature-dependent. The equations of motion are solved by a two-step perturbation technique to determine the nonlinear frequencies of the CNTRC panels. Numerical results demonstrate that the natural frequencies of the CNTRC panels are reduced but the nonlinear to linear frequency ratios of the CNTRC panels are increased as the temperature rises. In contrast, natural frequencies are increased but the nonlinear to linear frequency ratios are decreased by increasing the foundation stiffness. The results reveal that the natural frequencies are increased by increasing the CNT volume fraction, whereas the CNTRC panels with intermediate CNT volume fraction do not necessarily have intermediate nonlinear to linear frequency ratios.

1. Introduction

The exceptional mechanical, thermal and electrical properties of carbon nanotubes (CNTs) have allowed CNTs to be considered as significant reinforcement materials for high performance structural composites, especially for aeronautic and aerospace applications where the reduction of weight is crucial in order to reduce the fuel consumption and increase the payload. The theoretical and experimental investigation on the thermal–mechanical properties of carbon nanotube-reinforced composite (CNTRC) structures has increasingly become a hot research area for many engineers and material scientists in recent years. Due to their very attractive thermo-mechanical properties, these new materials will arise as key components in Micro-Electro-Mechanical Systems (MEMS) and Nano-Electro-Mechanical Systems (NEMS) [1,2]. Unlike the carbon fiber-reinforced composites, the CNTRCs can only contain a low percentage of CTNs (2–5% by weight) [3–6] as more volume fraction in CNTRCs can actually lead to the deterioration of their mechanical properties [7]. Shen [8] proposed to apply the functionally graded (FG) concept to CNTRCs in order to effectively make use of the low percentage of CNTs in the composites. He studied the nonlinear bending behavior of CNTRC plates with a linear distribution of CNTs along the thickness direction of the plates and observed that the load-bending moment curves of the plates can be considerably improved through the use of a functionally graded distribution of aligned CNTs in the matrix. Shen and his co-authors [9–12] further extended the study to the compressive and thermal postbuckling, and nonlinear free and forced vibration of CNTRC plates and highlighted the influence of the FG-CNT distribution patterns on the mechanical behaviors of the CNTRC structures. The concept of functionally graded nanocomposites is strongly supported by a recent publication [13] in which a functionally graded CNT reinforced aluminum matrix composite was fabricated by a powder metallurgy route. Consequently, investigations on bending, buckling and vibration of CNTRC structures are recently emerged as an interesting field of study [14–20].

Several studies have been reported on the postbuckling and nonlinear vibration of CNTRC cylindrical shells based on a higher order shear deformation theory [21–25]. However, relatively few researches have been made on the buckling and vibration of CNTRC cylindrical panels. Among those, Aragh et al. [26] studied linear free vibration of functionally graded CNTRC cylindrical panels based on the Eshelby–Mori–Tanaka approach. Jam et al. [27] and

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Yas et al. [28] investigated linear free vibration of functionally graded CNTRC cylindrical panels based on the Voigt model as the rule of the mixture. In their analysis, formulations are based on 3-D elasticity and solved by using differential quadrature method. In the aforementioned studies [26–28], however, the effective material properties of CNTRCs are assumed to be independent of temperature. To the best of the authors' knowledge, there is no literature covering nonlinear flexural vibration response of CNTRC cylindrical panels, in particular for the case of the panels resting on an elastic foundation.

The nonlinear flexural vibration behavior of isotropic and composite laminated cylindrical panels has received considerable attention [29–32]. However, although in a well-known reference case there seems to be a reasonable agreement for a flat plate, there are unresolved discrepancies between the results obtained by different authors for a cylindrical panel [29–32]. Unlike flat plates, the curves of nonlinear frequency as a function of amplitude of curved panels might be hardening or softening type [29–32]. It is mentioned that the governing differential equations for an FG-CNTRC cylindrical shell are identical in form to those of unsymmetric cross-ply laminated shells [24]. However, it remains unclear whether the CNTRC cylindrical panels still display a hardening nonlinearity under a low CNT volume fraction and this motivates the current investigation.

In the present work, we focus our attention on the nonlinear flexural vibration of CNTRC cylindrical panels resting on elastic foundations in thermal environments. Two kinds of CNTRC cylindrical panels, namely, uniformly distributed (UD) and functionally graded (FG) reinforcements, are considered. The equations of motion are based on a higher-order shear deformation theory with a von Kármán-type of kinematic nonlinearity. The panel-foundation interaction and thermal effects are also included. The material properties of CNTRCs are assumed to be temperature-dependent. The material properties of FG-CNTRCs are assumed to be graded in the thickness direction, and are estimated through a micromechanical model. A two-step perturbation technique is employed to determine the linear and nonlinear frequencies of the CNTRC panels. The numerical illustrations show the nonlinear vibration characteristics of CNTRC panels resting on Pasternak elastic foundations under different sets of environmental conditions.

2. Multi-scale model for vibration of CNTRC panels

Consider a CNTRC cylindrical panel resting on an elastic foundation. The panel is exposed to elevated temperature and is subjected to a transverse dynamic load $q(X, Y, \bar{t})$. The panel is referenced to a coordinate system (X, Y, Z) in which X and Y are in the axial and circumferential directions of the panel and Z is in the direction of the inward normal to the middle surface, and the corresponding displacements are designated by $\overline{U}$, $\overline{V}$, and $\overline{W}$. $\overline{\Psi}_x$ and $\overline{\Psi}_y$ are the rotations of the normals to the middle surface with respect to the Y- and X- axes, respectively. The origin of the coordinate system is located at the corner of the panel in the middle plane. As shown in Fig. 1, R is the radius of curvature, h the panel thickness, a the length in the X direction, and b the length in the Y direction, respectively. As is customary [29], the foundation is assumed to be a compliant foundation, which means that no part of the panel lifts off the foundation in the large amplitude vibration region. The load–displacement relationship of the foundation is assumed to be $p_0 = \overline{K}_1\overline{W} - \overline{K}_2\nabla^2\overline{W}$, where p_0 is the force per unit area, $\overline{K}_1$ is the Winkler foundation stiffness and $\overline{K}_2$ is the shearing layer stiffness of the foundation, and ∇^2 is the Laplace operator in X and Y. Let $\overline{F}(X, Y)$ be the stress function for the stress resultants defined by $\overline{N}_x = \overline{F}_{,YY}$, $\overline{N}_y = \overline{F}_{,XX}$ and $\overline{N}_{xy} = -\overline{F}_{,XY}$, where a comma denotes partial differentiation with respect to the corresponding coordinates.

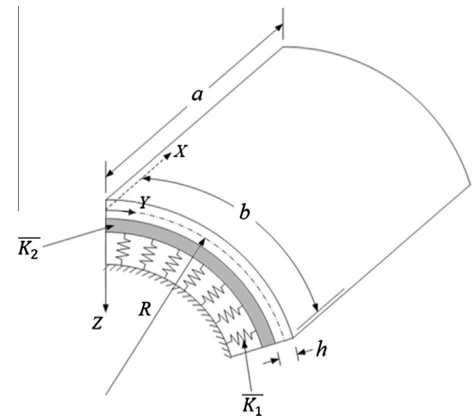

Fig. 1. Geometry and coordinate system of cylindrical panel on a Pasternak elastic foundation.

Based on the Sanders shell theory, Reddy and Liu [33] developed a simple higher order shear deformation shell theory. This theory assumes that the transverse shear strains are parabolically distributed across the shell thickness. The advantages of this theory over the first order shear deformation theory are that the number of independent unknowns ($\overline{U}, \overline{V}, \overline{W}, \overline{\Psi}_x$ and $\overline{\Psi}_y$) is the same as in the first order shear deformation theory, but no shear correction factors are required. Based on Reddy's higher order shear deformation theory with a von Kármán-type of kinematic nonlinearity and including panel-foundation interaction and thermal effects, the motion equations for an FG-CNTRC cylindrical panel can be derived in terms of a stress function $\overline{F}$, two rotations $\overline{\Psi}_x$ and $\overline{\Psi}_y$, and a transverse displacement $\overline{W}$. They are

$$\widetilde{L}_{11}(\overline{W}) - \widetilde{L}_{12}(\overline{\Psi}_x) - \widetilde{L}_{13}(\overline{\Psi}_y) + \widetilde{L}_{14}(\overline{F}) - \widetilde{L}_{15}(\overline{N}^T) - \widetilde{L}_{16}(\overline{M}^T) - \frac{1}{R}\overline{F}_{,XX} + \overline{K}_1\overline{W} - \overline{K}_2\nabla^2\overline{W} = \widetilde{L}(\overline{W}, \overline{F}) + \widetilde{L}_{17}(\ddot{\overline{W}}) - \left(\widetilde{I}_5\frac{\partial\ddot{\overline{\Psi}}_x}{\partial X} + \widetilde{I}'_5\frac{\partial\ddot{\overline{\Psi}}_y}{\partial Y}\right) + q \tag{1}$$

$$\widetilde{L}_{21}(\overline{F}) + \widetilde{L}_{22}(\overline{\Psi}_x) + \widetilde{L}_{23}(\overline{\Psi}_y) - \widetilde{L}_{24}(\overline{W}) - \widetilde{L}_{25}(\overline{N}^T) + \frac{1}{R}\overline{W}_{,XX} = -\frac{1}{2}\widetilde{L}(\overline{W}, \overline{W}) \tag{2}$$

$$\widetilde{L}_{31}(\overline{W}) + \widetilde{L}_{32}(\overline{\Psi}_x) - \widetilde{L}_{33}(\overline{\Psi}_y) + \widetilde{L}_{34}(\overline{F}) - \widetilde{L}_{35}(\overline{N}^T) - \widetilde{L}_{36}(\overline{S}^T) = \widehat{I}_5\frac{\partial\ddot{\overline{W}}}{\partial X} - \widehat{I}_3\ddot{\overline{\Psi}}_x \tag{3}$$

$$\widetilde{L}_{41}(\overline{W}) - \widetilde{L}_{42}(\overline{\Psi}_x) + \widetilde{L}_{43}(\overline{\Psi}_y) + \widetilde{L}_{44}(\overline{F}) - \widetilde{L}_{45}(\overline{N}^T) - \widetilde{L}_{46}(\overline{S}^T) = \widehat{I}'_5\frac{\partial\ddot{\overline{W}}}{\partial Y} - \widehat{I}'_3\ddot{\overline{\Psi}}_y \tag{4}$$

in which

$$\widetilde{L}(\ ) = \frac{\partial^2}{\partial X^2}\frac{\partial^2}{\partial Y^2} - 2\frac{\partial^2}{\partial X\partial Y}\frac{\partial^2}{\partial X\partial Y} + \frac{\partial^2}{\partial Y^2}\frac{\partial^2}{\partial X^2} \tag{5a}$$

$$\widetilde{L}_{17}(\ ) = -I_1 - \left(\widetilde{I}_7\frac{\partial^2}{\partial X^2} + \widetilde{I}'_7\frac{\partial^2}{\partial Y^2}\right) \tag{5b}$$

and the other linear operators $\widetilde{L}_{ij}(\ )$ are defined as in [21,22]. Note that the geometric nonlinearity in the von Kármán sense is given in terms of $\widetilde{L}(\ )$ in Eqs. (1) and (2). I_j, $\widehat{I}_j$ and $\widetilde{I}_j$ are defined in Eq. (16d) below. It is worthy to note that the motion Eqs. (1)–(4) for an FG-CNTRC cylindrical panel are identical in form to those of unsymmetric cross-ply laminated panels.

In the above equations, the superposed dots indicate differentiation with respect to time. $\overline{N}^T$, $\overline{M}^T$, $\overline{S}^T$, and $\overline{P}^T$ are the