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Strain gradient shell model for nonlinear vibration analysis of visco-elastically coupled Boron Nitride nano-tube reinforced composite micro-tubes conveying viscous fluid

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ABSTRACT

In the present research, nonlinear vibration in a coupled system of Boron-Nitride nano-tube reinforced composite (BNNTRC) micro-tubes conveying viscous fluid is studied. Single-walled Boron-Nitride nano-tubes (SWBNNTs) are arranged in a longitudinal direction inside Poly-vinylidene fluoride (PVDF) matrix. Damping and shearing effects of surrounded medium are taken into account by visco-Pasternak model. Based on piezoelectric fiber reinforced composite (PFRC) theory, properties of smart coupled BNNTRC micro-tubes are obtained. To enhance the accuracy of results, strain gradient theory is developed in cylindrical shell model, and the motion equations as well as the boundary conditions are derived using Hamilton's principle. Considering slip flow regime, the effects of various parameters such as Knudsen number, volume fraction and orientation angle of fibers, temperature change, viscosity and density of fluid on stability of coupled BNNTRC micro-tubes are investigated. Results indicate that stability of smart composite system is strongly dependent on orientation angle and volume percent of BNNTs. Results of this investigation can be applied for optimum design of shell and tube heat exchangers in micro scale.

1. Introduction

In the past several years, many researchers have focused on nano-tube reinforced composite properties and discovered that mechanical, electrical and thermal properties of polymer composites can be significantly improved when small percent of nano-tube such as carbon nano-tubes (CNTs) and BNNTs are added as fibers. Although the main purpose of these investigations are the development of this advanced material in actual structures.

BNNTs show appealing mechanical properties like CNTs due to similarity in structural. In spite of these similarities, BNNTs are different from CNTs in other aspects. BNNTs possess nearly uniform electronic properties that are not sensitive to their diameters and chiralities. It was shown that BNNTs would have a larger low-temperature thermal conductivity and high resistance to oxidation than CNTs [1]. Piezoelectricity is another fascinating property of BNNTs. This phenomenon is due to the rolling of the planar hexagonal BN networks to form tubular structures theoretically. Comparison of the axial normal stress and shear stress in BNNT- and CNT-based composite reveals that BNNT can carry much higher range of axial normal and shear stresses compared to CNT for the similar applied external load (electrical field) [2]. Premium features of nano-tubes (high strength and stiffness) causes to utilize it as reinforcement instead of conventional fibers in nano/micro-composite structures such as beam, plate and shell. Introduction of BNNT as a piezoelectric material which have coupled the electro-mechanical effects into polymer matrix, upgrade the application of nano/micro-composites and make a system of smart materials. Compared to CNTs, BNNTs are more suitable reinforcement candidate materials in composite structures because of these outstanding mechanical properties. Obviously, these properties make BNNTs very attractive for innovative applications in various branches of science and technology.

In recent years, various researches have been done to analyzing the buckling, dynamic stability, and free vibration of the smart structures in which the shell theory have been employed. Salehi-Khojin and Jalili [3] studied the buckling behavior of BNNT

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reinforced PVDF under combined electro-thermo-mechanical loadings by considering the effect of piezoelectric property of BNNT. Their results show that applying direct and reverse voltages to BNNT changes the buckling loads for any axial and circumferential wave numbers. Free vibration and buckling analysis of composite cylindrical shells conveying hot fluid was studied by Kadoli and Ganesan [4]. Their results demonstrated that the influence of fiber angle on the critical mean axial velocities is considerable. A three-dimensional solution of smart laminated anisotropic circular cylindrical shells with imperfect bonding was presented by Wang and Zhang [5]. Based on nonlocal piezo-electricity theory, vibration and buckling behavior of double-walled Boron-Nitride nano-tubes (DWBNNTs) embedded in an elastic medium with and without fluid was studied by Ghorbanpour Arani et al. [6–8]. They showed that the electric field effect on the frequency is approximately constant, while it decreases with increasing temperature. Also, they concluded that the electric field and its direction affect the magnitude of the critical buckling load. In another work, Ghorbanpour Arani et al. [9] researched into the nonlinear nonlocal vibration and instability of conveyed micro-tube reinforced by BNNT using Donnell's shell theory. Their results show that increasing volume fraction and orientation angle of fiber causes to increase stiffness of micro-tube.

Using generalized differential quadrature method (GDQM), Shu [10] investigated free vibration of composite conical shell reinforced with a piezoelectric layer. Free vibration response of composite sandwich cylindrical shell with flexible core is studied by Rahmani et al. [11]. Their results revealed that the sandwich shells with flexible core exhibit a complex behavior and the vibration patterns of the sandwich cylindrical shells are more complex than those of the homogeneous shells. Furthermore, it was observed that the natural modes of the sandwich shell are different from those of the sandwich plate and have a mixed mode nature. Amabili et al. [12,13] researched fluid filed tubes besides conveying fluid and empty tubes as a circular cylindrical shell.

However, vibration analysis of coupled system of BNNTRC micro-tubes conveying viscous fluid embedded in an elastic medium is a novel topic that it has not been found in literature. Motivated by these considerations, our aim is to study of electro-thermal vibration analysis of coupled composite micro-tubes which is placed in uniform temperature and electric fields. Micro-tubes are simulated by cylindrical shell model and they have been coupled together with visco-Pasternak medium including spring, shearing and damping constants. For the first time, strain gradient theory is developed for cylindrical shell model. Higher-order motion equations have been derived based on Hamilton's principle and differential quadrature method (DQM) is applied to obtain vibrational response of coupled composite micro-tube system. The results of this study is hoped to be used in design of smart controller such as heat exchanger and etc.

2. Constitutive equations based on PEFRC theory

To obtain properties of coupled composite micro-tubes, a representative volume element (RVE) has been considered and micro-mechanical method known as "XY PEFRC" or "YX PEFRC" [14,15] is employed. In this modeling both matrix and reinforcements are assumed to be smart and the BNNTs are considered as longitudinal straight fibers in both micro-tubes. The constitutive equations for the electro-thermo-mechanical behavior of the selected RVE according to the XYPEFRC micro-mechanical method are expressed as [9]:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \\ D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 & 0 & 0 & -e_{31} \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 & 0 & 0 & -e_{32} \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 & 0 & 0 & -e_{33} \\ 0 & 0 & 0 & C_{44} & 0 & 0 & 0 & -e_{24} & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 & -e_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{15} & 0 & \in_{11} & 0 & 0 \\ 0 & 0 & 0 & e_{24} & 0 & 0 & 0 & \in_{22} & 0 \\ e_{31} & e_{32} & e_{33} & 0 & 0 & 0 & 0 & 0 & \in_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \\ E_1 \\ E_2 \\ E_3 \end{Bmatrix} - \begin{Bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ p_1 \\ p_2 \\ p_3 \end{Bmatrix} \Delta\Theta, \tag{1}$$

where $\{\sigma_i\}$, $\{\tau_{ij}\}$, $\{\varepsilon\}$, $\{\gamma_{ij}\}$, $\{D\}$ and $\{E\}$ are normal stresses, shear stresses, normal strains, shear strains, electric displacement and electric field vectors, respectively. Also, $[C]$, $[e]$ and $[\in]$ are matrix of elastic stiffness, piezoelectric and dielectric parameters respectively. Furthermore, the coefficients of thermal expansion and pyroelectric are shown by $\{\lambda\}$ and $\{p\}$, respectively, and the temperature change is represented by $\Delta\Theta$. Assuming plane stress condition and unidirectional electric field along the micro-tube [9], Eq. (1) can be simplified as follows:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{\theta\theta} \\ \tau_{x\theta} \\ D_x \end{Bmatrix} = [Q] \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{\theta\theta} \\ \gamma_{x\theta} \\ E_x \end{Bmatrix} - \begin{Bmatrix} \lambda_{xx} \\ \lambda_{\theta\theta} \\ \lambda_{x\theta} \\ p_x \end{Bmatrix} \Delta\Theta, \tag{2}$$

where x, y and z are longitudinal, circumferential and transverse coordinates with the origin located at the mid-plane of the micro-tubes and matrix $[Q]$ is defined as:

$$[Q] = \begin{bmatrix} C_{xxxx} & C_{xx\theta\theta} & 0 & -e_{xxx} \\ C_{xx\theta\theta} & C_{\theta\theta\theta\theta} & 0 & -e_{x\theta\theta} \\ 0 & 0 & C_{x\theta x\theta} & 0 \\ e_{xxx} & e_{x\theta\theta} & 0 & \in_x \end{bmatrix}. \tag{3}$$

All the coefficients of above matrix are mentioned in Appendix A. The longitudinal component of electric field in terms of electric potential is defined as [9]:

$$E_x = -\frac{\partial \phi}{\partial x}. \tag{4}$$

where ϕ denotes the scalar function of electric potential. To consider the effects of orientation angle of the BNNTs with respect to longitudinal axis, the following transformation matrix can be employed as:

$$[\widetilde{Q}] = [T][Q][T]^T. \tag{5}$$

The transformation matrix [T] is given by [16] as:

$$[T] = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & 2\sin\alpha\cos\alpha & 0 \\ \sin^2\alpha & \cos^2\alpha & 2\sin\alpha\cos\alpha & 0 \\ -\sin\alpha\cos\alpha & \sin\alpha\cos\alpha & \cos^2\alpha - \sin^2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

where α is the angle of BNNTs with respect to micro-tube axis.

3. Strain gradient shell theory (SGST)

Fig. 1 demonstrates two composite micro-tubes which are coupled with visco-Pasternak medium. PVDF and BNNTs are selected as a matrix and reinforcement, respectively. Both micro-tubes are conveying viscose fluid and nonlinear vibration of coupled smart system is investigated using SGST.

The displacement components of cylindrical shell $\widetilde{U}_i$, $\widetilde{V}_i$ and $\widetilde{W}_i$ in the axial x, circumferential θ and radial z directions, respectively, can be written as [17]: