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Electro-thermal vibration of a smart coupled nanobeam system with an internal flow based on nonlocal elasticity theory

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ABSTRACT

In this study, nonlinear vibration and stability of a fluid-conveying nanotube (FCNT), elastically coupled to a smart piezoelectric polymeric beam (PPB) is investigated based on nonlocal elasticity theory, Euler–Bernoulli beam model and energy approach. In order to obtain an active instability control of FCNT, the PPB is longitudinally polarized as an actuator while in the absence of an imposed electric field it is also possible to be used as an alarm biosensor. Simulating the above smart coupled nanobeam system alike the double nanobeam systems (which are relatively developed by other authors) leads to obtain nonlinear differential equations of motion. The linear natural and damping frequencies are achieved by ignoring all the system nonlinearities which are then considered to obtain nonlinear frequencies using an iterative method. The effects of geometric nonlinearity, small scale parameter, coupled medium constants, Knudsen number, temperature change, aspect ratio and external applied voltage on critical flow velocity are studied in details. It is concluded that applying an electric voltage on PPB will increase the stability of FCNT. It is hoped that this research will provide a new approach to smart instability control of FCNTs which is no yet reported.

1. Introduction

It is commonly believed that the nanotechnology will spark a series of industrial revolutions in the following decades and the discovery of nanotubes (e.g. carbon nanotubes in 1991 [1] and boron nitride nanotubes in 1995 [2]) is one of the most significant breakthroughs that could accelerate the development of nanotechnology. In general, nanotechnology encompasses the production and application of physical, chemical and biological systems in the nanometer–micrometer range, as well as the integration of the resulting nanostructures into larger systems to fabricate novel nanodevices [3,4]. Recently, the nanotubes with an internal fluid have been attracted more attention amongst researchers due to their widespread potential applications in biological systems (e.g. biosensing, biological separation, molecular imaging), medicine (e.g. drug delivery), chemistry (e.g. chemical experiments, fuel cells), physics (e.g. optomechanical systems) and other engineering fields [5–7]. In this regard, the fluid induced vibration, the vibration due to the flowing internal fluid, of FCNTs has been an area of active researches [8–10].

In addition, the recent interesting field of the nanotechnology is the complex coupled nanobeam systems (i.e. macro coupled beam systems) that includes connected two or more nanobeams [11] and can be used to fabricate novel potential electronic, optical, magnetic, mechanical, and chemical/biological devices with applications ranging from sensors to computation and control [12–15]. The nanobeams coupling connection of these systems are considered usually by an elastic medium (i.e. polymer gels) or van der Waals forces [16]. In this regard, Murmu and Adhikari [17] studied the nonlocal effects of the double-nanorod systems on the axial vibration. In their numerical analysis approach, the nonorod considered to be CNT and concluded that the fundamental natural frequency of axially vibrating nanorods has a decreasing nature with the increasing nonlocal parameter. In another work of these authors, the axial instability of double-nanobeam systems is also investigated [18]. Transverse vibration of the elastically connected-carbon nanotube system due to a moving nanoparticle is studied by Simsek [19]. He employed EB beam theory in the frame of nonlocal elasticity theory to simulate the coupled nanotube system. In a similar vision, Ghorbanpour and Roudbari [20] have investigated the nonlocal vibrations of a coupled boron nitride nanotubes (BNNTs) system under a moving nanoparticle based on piezoelastic theory and Euler–Bernoulli beam model. Altogether, according to the above discussion, lack of proper research to instability prediction as well as instability smart control of FCNTs can be clearly felt. Hence, in this study we aim to demonstrate a novel smart coupled nanobeam system (see Section 4) and then is analyzed to yield the vibration response of FCNT in presence of external voltage imposed on PPB.

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2. Piezoelectric constitutive relation for PPB

The subsequent characterization of electromechanical coupling covers the various classes of piezoelectric materials. Details with respect to definition and determination of the constants describing these materials have been standardized by the Institute of Electrical and Electronics Engineers [21]. In this regards, stresses and strains on the mechanical side, as well as flux density and field strength on the electrostatic side, may be combined as follows

$$\begin{Bmatrix} \sigma \\ D \end{Bmatrix} = \begin{bmatrix} C & -e \\ e^T & \in \end{bmatrix} \begin{Bmatrix} \varepsilon \\ E \end{Bmatrix} - \begin{Bmatrix} \lambda \\ p \end{Bmatrix} \Delta\Theta. \tag{1}$$

where $\{\sigma\}$, $\{\varepsilon\}$, $\{D\}$ and $\{E\}$ are stress, strain, electric displacement and electric field vectors, respectively, and $[C]$, $[e]$ and $\{\in\}$ are matrices of elastic stiffness, piezoelectric and dielectric constants, respectively. Furthermore, the coefficients of thermal expansion, pyroelectric and temperature change are shown by $\{\lambda\}$, $\{p\}$ and $\Delta\Theta$, respectively. Considering Euler–Bernoulli beam model for the PPB above constitutive equations are simplified as follows

$$\begin{Bmatrix} \sigma_x \\ D_x \end{Bmatrix} = \begin{bmatrix} C_{11} & -e_{11} \\ e_{11} & \in_{11} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ E_x \end{Bmatrix} - \begin{Bmatrix} \lambda_1 \\ p_1 \end{Bmatrix} \Delta\Theta . \tag{2}$$

where x denotes the longitudinal direction of the PPB. It is also noted that the longitudinal component of the electric field can be written in terms of electric potential ϕ as [22]

$$E_x = -\frac{\partial \varphi}{\partial x}. \tag{3}$$

3. Nonlocal elasticity theory

Small-scale effect is studied in nano and micro mechanics often using Eringen's nonlocal elasticity theory. Based on this theory, the stress and the electric displacement at a reference point depend not only on the components of the strain and electric-field at the same position, but also on all other points of the body. Thus, the well-known relations between nonlocal and classical stresses is expressed as [23]

$$\left(1-(e_0a)^2\nabla^2\right)\{\sigma\}_{\text{nonlocal}} = \{\sigma\}_{\text{classical}}, \tag{4}$$

and for the piezoelectric materials, we have [24,25]

$$\left(1-(e_0a)^2\nabla^2\right)\{\sigma\}_{\text{nonlocal}} = \{\sigma\}_{\text{classical}}, \tag{5 – a}$$

$$\left(1-(e_0a)^2\nabla^2\right)\{D\}_{\text{nonlocal}} = \{D\}_{\text{classical}}, \tag{5 – b}$$

where $\{\sigma\}$ and $\{D\}$ are respectively, the components of nonlocal stress and electric displacement tensors, e_0a is the small-scale parameter and ∇^2 represents the Laplace operator. The above implicit relations couple the nonlocal stress and electric displacement with the classical stress and electric displacement. To achieve explicit relations, an iterative-based method can be presented for the above equations as follows

$$\{\sigma\}^{i+1}_{\text{nonlocal}} = (e_0a)^2\nabla^2\{\sigma\}^{i}_{\text{nonlocal}} + \{\sigma\}_{\text{classical}}, \tag{6 – a}$$

$$\{D\}^{i+1}_{\text{nonlocal}} = (e_0a)^2\nabla^2\{D\}^{i}_{\text{nonlocal}} + \{D\}_{\text{classical}}, \tag{6 – b}$$

$$\{\sigma\}^{0}_{\text{nonlocal}} = \{\sigma\}_{\text{classical}}, \tag{6 – c}$$

$$\{D\}^{0}_{\text{nonlocal}} = \{D\}_{\text{classical}}, \tag{6 – d}$$

where i is the iteration number and the first iteration can be started by local results. It is clear that accuracy of the nonlocal results will be improved by increasing the number of iterations as is shown graphically in the numerical results section.

4. Modeling and kinematic of the smart coupled nanobeam system

Consider a vertically coupled nanobeam system as shown in Fig. 1. In the present study the carbon nanotube (CNT) containing steady nano-flow is considered as FCNT which is elastically coupled by an axially polarized PPB (e.g. made of poly-vinylidene fluoride [26]). The CNT and PPB are attached by innumerable longitudinal and vertical springs for modeling the effect of enclosing elastic medium, forces due to nanooptomechanical effects or van der Waals forces [12–15]. Different values of spring stiffness for different polymers can be used for the study. The Winkler spring modulus as well as Pasternak shear modulus in the Pasternak environment model are utilized for evaluating the stiffness of vertical and longitudinal springs, respectively [27–29]. Based on Euler–Bernoulli beam model [30], the components of axial and transverse displacement field, denoted by $\tilde{u}(x,z,t)$ and $\tilde{w}(x,z,t)$ respectively, for both of CNT and PPB are expressed as

$$\begin{cases} \tilde{u}^i(x,z,t) = u^i(x,t) - z\frac{\partial w^i(x,t)}{\partial x} \\ \tilde{w}^i(x,z,t) = w^i(x,t) \end{cases} \quad i: C \text{ and } P, \tag{7}$$

where u and w are the components of the middle surface displacement (i.e., displacement at $z=0$) and x and z are the coordinates taken along the length and the thickness of the beams (see Fig. 2). Additionally, the super indexes C and P indicate the CNT and PPB, respectively. The non-zero strain–displacement relationships for both of CNT and PPB and by omitting the large strain terms except the square of $(\partial w/\partial x)$ (which indicates the rotation of a transverse normal line in the beam), are given by

$$\varepsilon^i_x = \frac{\partial u^i}{\partial x} + \frac{1}{2}\left(\frac{\partial w^i}{\partial x}\right)^2 - z\frac{\partial^2 w^i}{\partial x^2}. \quad i: C \text{ and } P \tag{8}$$

5. Energy functions

5.1. Energy associated with CNT

The elastic strain energy of CNTs is given by

$$U^C = \frac{1}{2}\iiint_{\forall^C} \varepsilon^C_x \sigma^C_x \, d\forall, \tag{9}$$

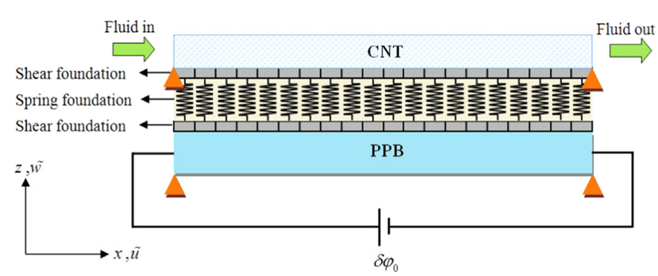

Fig. 1. Schematic representation of the elastically coupled system conveying fluid flow.

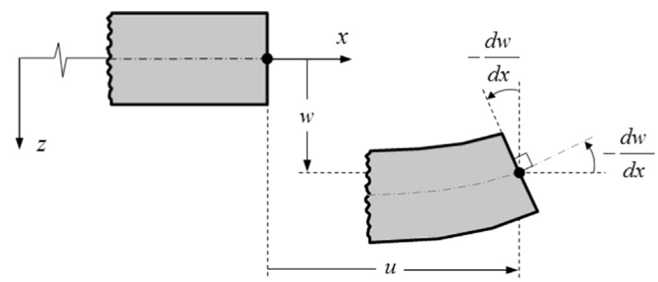

Fig. 2. Kinematics of Euler–Bernoulli beam theory.