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Nonlocal piezoelastic surface effect on the vibration of visco-Pasternak coupled boron nitride nanotube system under a moving nanoparticle

A. Ghorbanpour Arani [a,b,*], M.A. Roudbari [a]

[a] Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran
[b] Institute of Nanoscience & Nanotechnology, University of Kashan, Kashan, Iran

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ABSTRACT

In this article, the nonlocal longitudinal and transverse vibrations of coupled boron nitride nanotube (BNNT) system under a moving nanoparticle using piezoelastic theory and surface stress based on Euler–Bernoulli beam are developed. BNNTs are coupled by visco-Pasternak medium and single-walled zigzag structure BNNT is selected in this study. Hamilton's principle is employed to derive the corresponding higher order equations of motion for both nanotubes. The detailed parametric study is conducted, focusing on the remarkable effects of the small scale parameter, aspect ratio, surface stress and visco-Pasternak coefficients on the vibration behavior of the coupled BNNT system. Also it is demonstrated that the normalized dynamic deflections obtained by using the classical beam theory are smaller than those obtained by the nonlocal beam theory. The influence of the smart controller is proved on the nondimensional fundamental longitudinal frequency. The result of this study can be useful to manufacture of smart microelectromechanical system and nanoelectromechanical system in advanced biomechanics applications with electric field as a parametric controller.

1. Introduction

One of the most promising materials for nanotechnology is boron nitride nanotubes (BNNTs) due to the coupling characteristics of electromechanics field. The structure of BNNTs is similar to the structure of carbon nanotubes (CNTs) where carbon atoms are substituted by boron and nitrogen atoms. CNTs are made of a sheet of carbon atoms rolled as a tube, where they are simulated by different continuum theories such as Euler–Bernoulli beam (EBB), Timoshenko beam (TB) and shell models [1–3]. Limited studies have been reported about BNNTs in the literature [4–10]. Extraordinary properties for BNNTs such as high elastic modulus, high thermal conductivity, low density, constant wide band gap, superb structural stability and chemical inertness have been proved [11].

Nowadays, a large amount of research works has been carried out on the buckling, vibration and wave propagation of the nanotubes/microtubes with and without moving nanoparticle. Transverse vibrations of single-walled carbon nanotube (SWCNT) and double-walled carbon nanotube (DWCNT) under axial load using EBB, TB and Donnell shell models were studied by Ghorbanpour Arani et al. [1] who showed that natural frequency of SWCNTs increases with increasing the axial half sine wave number and the difference between the nonlocal and local theories increases at high axial half sine wave number. Moreover, they concluded that for the DWCNTs, the nonlocal theory predictions for the natural frequency are lower than those of the classical theory. Also, Ghorbanpour Arani et al. [7] investigated thermal influence on the buckling of the DWCNT subjected to a uniform external pressure. The surrounding elastic medium was modeled by Pasternak foundation. A generalized nonlocal beam theory to study of the bending, buckling and free vibration of different beam theories was proposed by Aydogdu [12] who investigated the effects of small scale parameter and the length of nanobeam.

Furthermore, the dynamic analysis of CNTs on the movement of nanoparticles has been addressed in the literature. Dynamic response of a SWCNT subjected to a moving nanoparticle was studied in the framework of the nonlocal continuum theory by Kiani [13], who considered the inertial effects of the moving nanoparticle and the existing friction between the nanoparticle surface and the inner surface of the SWCNT. Simsek [14] proposed the analytical and numerical solution procedures for vibration of an embedded microbeam under moving a microparticle based on the modified couple stress theory and EBB. The influences of the material length scale parameter, the Poisson's ratio, the velocity of the microparticle and the elastic medium constant on the dynamic responses of the microbeam were investigated. An analytical method of the small scale parameter on the vibration of single-walled boron nitride nanotube (SWBNNT) under a moving nanoparticle is presented by Ghorbanpour Arani et al. [8]. In this article, the effects of electric field, elastic medium, slenderness ratio and small scale parameter are investigated on the vibration behavior of

* Corresponding author at: Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran. Tel.: +98 361 5912450; fax: +98 361 5912424.
E-mail addresses: aghorban@kashanu.ac.ir, a_ghorbanpour@yahoo.com (A. Ghorbanpour Arani).

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SWBNNT under a moving nanoparticle. Results indicated the importance of using surrounding elastic medium in the decrease of normalized dynamic deflection.

In recent years, many investigations have been carried out on the influence of surface stress on the nanotubes. The stress and deformation properties of nanostructures can be affected by surface effects. It is interesting to note that, since the surface to volume ratio is very large at nanoscale, considering the effects of surface parameters is necessary. Wang [15] worked on the vibration analysis of fluid conveying nanotubes with consideration of surface effects. In a different model, the effects of both inner and outer surface layers on the nanotubes are taken into consideration. He showed that the surface effects with positive elastic constant or positive residual surface tension tend to increase the natural frequency and critical flow velocity. For small tube thickness or large aspect ratio, the stability of the nanotubes will be greatly enhanced due to the surface effect. The natural frequency of nanotubes with consideration of surface effects was studied by Lee [16] using the nonlocal TB theory. They showed that the effect of surface stresses on the natural frequency of the nanotube is very significant. Ansari and Sahmani [17] proposed a non-classical solution to analyze bending and buckling responses of nanobeams including surface stress effects. Their results are presented to demonstrate the difference between the behaviors of the nanobeam predicted by the classical and non-classical solutions which depends on the magnitudes of the surface elastic constants. Surface effects on the vibrational frequency of DWCNTs using the nonlocal TB model were proposed by Lei et al. [18]. In this paper, the influence of the surface elasticity modulus, residual surface stress, nonlocal parameter, axial half-wave number and aspect ratio is investigated in detail.

With respect to developmental works on analysis of coupled systems, it should be noted that none of the research mentioned above, has considered coupled double-nanotube and nanobeam-systems. Murmu and Adhikari [19] presented an investigation on the longitudinal vibration of a double-nanorod-system (DNRS) based on analytical method for clamped–clamped and clamped–free boundary conditions. Their results highlighted that the nonlocal effect considerably influences the axial vibration of DNRS. Expressions for free bending-vibration of double-nanobeam-system (DNBS) were established by Murmu and Adhikari [20] within the framework of Eringen's nonlocal elasticity theory. They found that the nonlocal natural frequencies of DNBS are smaller when compared to the corresponding local frequency values. The axial instability of DNBS ems is investigated by Murmu and Adhikari [21] based on Eringen's nonlocal elasticity theory and EBB model. They concluded that the increase of the stiffness of the coupling elastic medium in DNBS reduces the small-scale effects during the out-of-phase buckling modes. Simsek [22] presented an analytical method for the forced vibration of an elastically connected double-carbon nanotube system (DCNTS) carrying a moving nanoparticle based on the nonlocal elasticity theory. He showed that the velocity of the nanoparticle and the stiffness of the elastic layer have significant effects on the dynamic behavior of DCNTS. Surface effects on the transverse vibration and axial buckling of DNBS were examined by Wang and Wang [23] based on a refined EBB model. It is found that surface effects get quite important when the cross-sectional size of beams shrinks to nanometers. A state-space form for studying transverse vibrations of DNBSs, made of two outer elastic beams continuously joined by an inner viscoelastic layer, was presented by Palmeri and Adhikari [24] based on Galerkin-type approximations. Numerical examples demonstrate that the proposed approach is accurate and versatile, and lends itself to be used for both frequency- and time-domain analyses.

Motivated by these considerations, this study aims to present a comprehensive model for nonlocal piezoelastic surface effect on the longitudinal and transverse vibration of visco-Pasternak coupled BNNT system under a moving nanoparticle. Coupled SWBNNTs are embedded with viscoelastic medium where simulated by visco-Pasternak type as spring, shear and damping foundations. The influences of surface stress, aspect ratio, viscoelastic medium stiffness and small scale parameter on nonlocal vibration behavior of coupled SWBNNTs have been taken into account. The result's output of this study can be significant influence in design and produce of micro electro mechanical system (MEMS) and nanoelectro mechanical system (NEMS) for advanced applications.

2. Nonlocal piezoelastic theory

Fig. 1 depicts a zigzag coupled SWBNNT embedded in a visco elastic medium with loading configurations. The radius of the nanotubes is R, the length is L and the thickness is t. In order to express the equation of equilibrium in the terms of mechanical and electrical components of displacement, the stress–strain relation for piezoelectric materials is given by [10,25]:

$$\begin{aligned}\{\tau\} &= [C]\{\varepsilon\} - [e]^T\{E\},\\ \{D\} &= [e]\{\varepsilon\} + [\chi]\{E\},\end{aligned} \tag{1}$$

where $\{\tau\}$, $\{\varepsilon\}$, $\{E\}$ and $\{D\}$ are classical stress, strain, electric field and flux density, respectively. Likewise $[C]$, $[e]$ and $[\chi]$ denote elastic stiffness, piezoelectric and dielectric constants, respectively. The strain–displacement relation appropriate to EBB may be written as [17]

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2. \tag{2}$$

According to the nonlocal elasticity theory [26], the stress field at a point x in an elastic continuum depends not only on the strain field at the same point but also on strains at all other points of the body. The constitutive equation of the nonlocal elasticity then becomes

$$\left(1 - (e_0 a)^2 \nabla^2\right)\sigma = \tau, \tag{3}$$

where ∇^2 is the Laplacian operator. The above nonlocal constitutive Eq. (3) has been recently used widely for the study of micro and nanostructure elements. Therefore, the only nonzero nonlocal stress

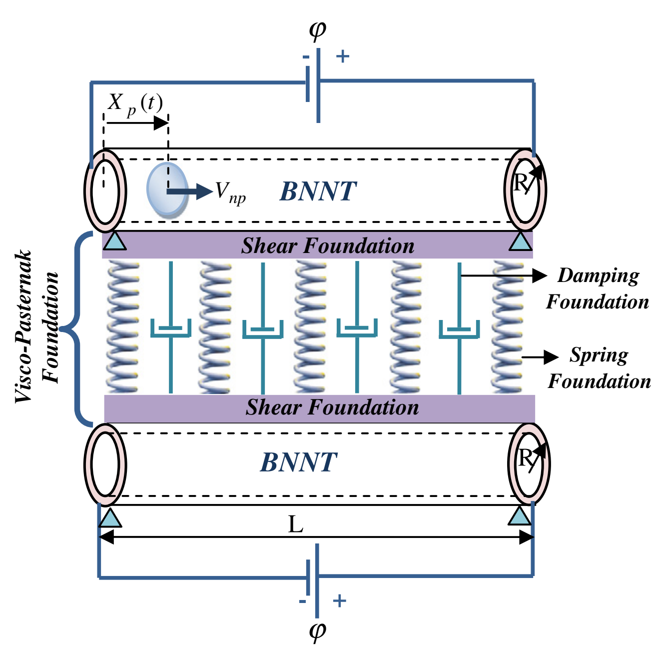

Fig. 1. Configuration of double-SWBNNT with electrical potential field and surface effect under moving nanoparticle.