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Surface stress, initial stress and Knudsen-dependent flow velocity effects on the electro-thermo nonlocal wave propagation of SWBNNTs

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ABSTRACT

This paper investigates the electro-thermal nonlocal wave propagation of fluid-conveying single-walled Boron Nitride nanotubes (SWBNNTs) using nonlocal piezoelasticity with surface stress, initial stress and Knudsen-dependent flow velocity effect. SWBNNT is embedded in a vicsoelastic medium which is simulated as visco-Pasternak foundation. Using Euler–Bernoulli beam (EBB) model, Hamilton's principle and nonlocal piezoelasticity theory, the higher order governing equation is derived. A detailed parametric study is conducted, focusing on the combined effects of the electric parameters, viscoelastic medium, initial stress, surface stress, Knudsen number (Kn) and small scale on the wave propagation behaviour of the fluid-conveying SWBNNT. The results show that for smaller values of wave number the dispersion relation for different fluid viscosities seems to be similar. At the higher values of wave numbers, increase in the wave frequency values is remarkable due to increase in fluid viscosity. The electric field as a smart controller, surface effect, initial stress, temperature change and slip velocity effect have significant role on the wave frequency. The results of this work is hoped to be of use in design and manufacturing of smart MEMS/NEMS in advanced medical applications such as drug delivery systems with great applications in biomechanics.

1. Introduction

BNNTs have become one of the most promising new structures for nanotechnology due to their novel electronic, thermal and mechanical properties. There is a similar atomic structure between BNNTs and carbon nanotubes (CNTs), whereas BNNTs have suitable resistance to oxidate and more stability. There are two theoretical models to analyze the structure of CNTs which are molecular dynamic method and continuum mechanics approach for small number of molecule or atoms and large-scale systems, respectively. BNNTs are semiconductors, because of the large band gaps regardless of chirality and diameter. So they play a dominant role as a significant material to be used of nanosized sensors and actuators, due to their unique structural, mechanical, thermal, electrical and chemical properties [1]. There are so many papers about wave propagation analysis and surface, initial stress and Knudsen number effect of CNTs in the literatures. Because the BNNTs have the perfect hollow cylindrical geometry, they can be applied in many potential applications to hold fluid and nano particles, for advanced medical applications such as drug delivery systems with great applications in biomechanics. Wu et al. [2] studied on the bending wave propagation of carbon nanotubes in a bi-parameter elastic matrix. They modelled CNTs as a nonlocal elastic beam, whereas the surrounding medium is modelled as a bi-parameter elastic medium. Likewise, a comparison of wave speeds using the Rayleigh and Euler–Bernoulli theories of beams with the results of molecular dynamics simulation indicates that the nonlocal Rayleigh beam model is more adequate to describe flexural waves in CNTs than the nonlocal Euler–Bernoulli model. The influences of the surrounding medium and rotary inertia on the phase speed for single-walled and double-walled CNTs were analyzed.

Effects of viscous fluid on wave propagation in carbon nanotubes were presented by Wang et al. [3], who found that numerical simulations are performed with the consideration of different scale coefficients to discuss the influence of the viscous fluid. From the results, it can be observed that the dispersion relation can be changed by the fluid viscosity obviously. Moreover, due to the fluid viscosity, the wave frequency will be reduced to a low region and the elastic wave behaviours can be significantly influenced by the viscous fluid velocity.

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. Surface effects on the

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vibrational frequency of double-walled carbon nanotubes using the nonlocal Timoshenko beam model were proposed by Lei et al. [4]. In this paper, the influence of the surface elasticity modulus, residual surface stress, nonlocal parameter, axial half-wave number and aspect ratio are investigated in detail.

Wang [5] worked on the vibration analysis of fluid-conveying nanotubes with consideration of surface effects. In a new 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.

Considering the initial stress in nanodevices is essential due to material properties mismatch, external load and surrounding medium. Wang et al. [6] investigated Scale effects on flexural wave propagation in nanoplate embedded in elastic matrix with initial stress. They considered the influences of the scale coefficient, the surrounding elastic matrix and the initial stress on the wave propagation properties. The results showed that the nonlocal model provides an appropriate method to investigate the characteristics of the flexural wave in the nanoplate. The effects of Knudsen-dependent flow velocity on vibrations of a nano-pipe conveying fluid is proposed by Mirramezani et al. [7], who investigated the effect of nano-flow on vibration of nano-pipe conveying fluid using Knudsen (Kn). They used Euler–Bernoulli plug-flow beam theory and modified no-slip condition of nano-pipe conveying fluid based on Kn. Also, they considered the effect of slip condition, for a liquid and a gas flow.

Unlike widely used CNTs and so many published literatures about it, there are few researches about BNNTs in the literature. Salehi-Khojin et al. [8] were proposed Buckling of BNNT reinforced piezoelectric polymeric composites subject to combined electro-thermo-mechanical loadings. They indicated that the support of piezoelectric matrix significantly enhances the buckling resistance of BNNT. Alternatively, the effect of BNNT piezoelectric property on the buckling behaviour of composites is demonstrated. Furthermore, it is demonstrated that the supporting effect of elastic medium depends on the direction of applied voltage and thermal flow. Electro-thermo-mechanical buckling of DWBNNTs embedded in bundle of CNTs using nonlocal piezoelasticity cylindrical shell theory has carried out by Ghorbanpour et al. [9], who found applying direct and reverse voltages to DWBNNT with and without considering elastic medium lead to decrease and increase nonlocal electro-thermo-mechanical buckling load, respectively. Also, the influence of the small length scale on the buckling load was investigated. It is concluded that the nonlocal buckling load decreases when considering the small scale parameter. Likewise, the results of this research can be used for studying the electro thermo-mechanical buckling behaviour of smart piezoelectric nanotubes such as multi-walled BNNTs is assumed to be surrounded by a bundle of CNTs as elastic medium for reinforcement. Transverse vibrations of SWCNT and DWCNT under axial load using Euler–Bernoulli, Timoshenko beam theory, and Donnell shell model were carried out by Ghorbanpour et al. [10], who showed that natural frequency of SWCNTs increases with increase in the axial half sine wave number and the difference between the non-local and local theories increases at high axial half sine wave number.

In the literature, there is no report on the electro-thermal nonlocal wave propagation of fluid-conveying SWBNNT using nonlocal piezoelasticity with surface, initial stress and Knudsen-dependent flow velocity effect. Motivated by these considerations, this research aims to study the slip velocity, initial stress and surface effect on the wave propagation of fluid-conveying BNNT which is surrounded by viscoelastic matrix for EBB theory with applied electric field and temperature change.

2. Nonlocal piezoelasticity theory

Fig. 1 depicts a zigzag SWBNNT embedded in an elastic medium with loading configurations. The radius of the nanotube 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 Ref. [11]

$$\{\tau\} = [C]\{\varepsilon\} - [e]^T\{E\}, \{D\} = [e]\{\varepsilon\} + [\lambda]\{E\}, \quad (1)$$

where $\{\tau\}$, $\{\varepsilon\}$, $\{E\}$ and $\{D\}$ are classical stress, strain, electric field and flux density, respectively. Likewise $[C]$, $[e]$ and $[\lambda]$ denote elastic stiffness, piezoelectric and dielectric constants, respectively. The strain–displacement relation appropriate to EBB may be written as Ref. [12]

$$\varepsilon_{xx} = -z\frac{\partial^2 w}{\partial x^2}. \quad (2)$$

According to the nonlocal elasticity theory [13], the stress field at a point x in an elastic continuum not only depends 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

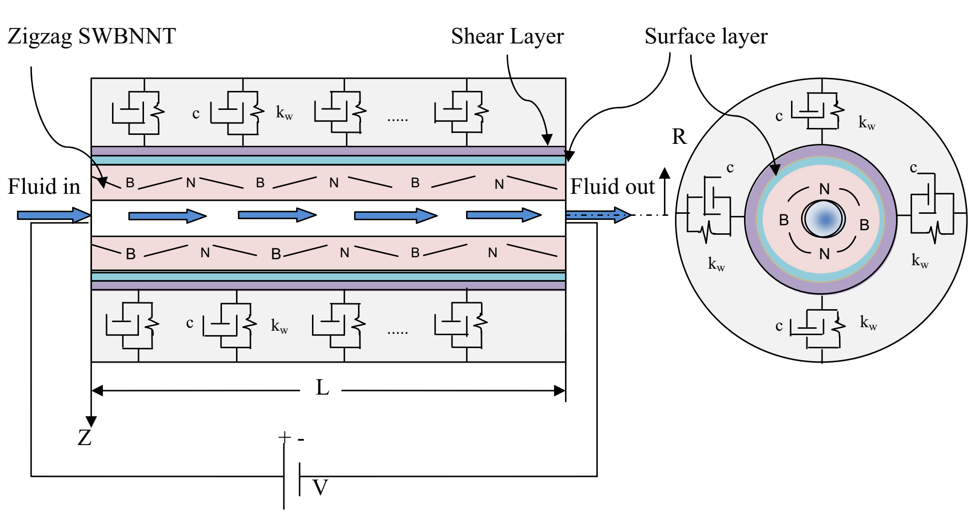

Fig. 1. Configuration of fluid-conveying SWBNNT with applied electric field and surface effect.