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Flow-induced vibration of double bonded visco-CNTs under magnetic fields considering surface effect

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ABSTRACT

Vibration of a double visco-elastic carbon nanotubes (CNTs) conveying viscous fluid coupled by visco-Pasternak medium is investigated based on visco-surface nonlocal theory. CNTs are placed in uniform longitudinal magnetic field and modeled by Euler–Bernoulli beam (EBB) theory. Visco-CNTs are conveying viscous fluid in which the effect of slip boundary condition is considered using Knudsen number correct factor in Navier–Stokes relations. The higher order governing equations of motion are derived based on Hamilton's principle where differential quadrature (DQ) approach is applied to obtain the nonlocal frequency of coupled visco-CNTs system. The detailed parametric study is conducted, focusing on the combined effects of the magnetic field, visco-Pasternak foundation, Knudsen number, surface effect, aspect ratio, velocity of conveying viscous fluid and direct of fluid velocity. Also, it is found that trend of figures have good agreement with previous researches. The results of this work could be used in design and manufacturing of nano/micro mechanical system in advanced biomechanics applications with magnetic field as a parametric controller.

1. Introduction

Ever since the CNTs were discovered by Iijima [1] in 1991, more researches have been published in the literature about vibration, buckling and wave propagation of nanotubes. Nano structural elements include nanotubes, nanobeams, nanoplates, nanosheets and nanocones. Nano structure components have widely applications in micro/nano electromechanical systems (MEMS/NEMS), sensors, actuators, fluid storage, fluid transport and drug delivery systems [2]. Due to its potential, nanotubes are used in nano technology, particularly in recent years utilized in vibration of carbon nanotubes with/without conveying fluid.

In this regard, Murmu and Pradhan [3] investigated the thermal vibration of single walled carbon nanotubes (SWCNTs) based on thermo-nonlocal elasticity theory. They considered Winkler-type to simulation of surrounding elastic medium. Their result indicated that the nonlocal parameter, stiffness elastic medium and temperature change have effect on vibration modes and nonlocal frequency. Vibration analysis of double-walled carbon nanotubes (DWCNTs) basedon nonlinear EB and nonlocal elasticity theories was studied by Fang et al. [4]. They considered clamped–clamped condition and used Hamilton's principle to drive nonlinear equations of motion. In this paper, the influences of nonlocal parameters, nonlinear van der Waals forces, aspect ratio and Winkler constant were discussed on nonlinear coaxial and noncoaxial vibration. Wang and Ni [5] used EB classical beam to modeling the nanotubes as a continuum structure conveying viscous fluid. They found that the effect of fluid viscosity on the vibration and instability of CNTs can be ignored but increasing the velocity of flow fluid has remarkable effect on frequency and stability of CNTs. Kuang et al. [6] reported the effect of nonlinear geometry and van der Waals force on the vibration of DWCNT conveying fluid. They indicated that the coupling between longitudinal and transverse displacements has little effect on the dynamic vibration. Ghorbanpour Arani et al. [7] investigated vibration of DWCNT embedded in an elastic medium and subjected to an axial fluid flow using shell theory. They solved the higher-order governing equations by Galerkin and averaging methods. Elastic medium, small scale parameter, velocity and density of fluid were taken into account to calculate the effects of axial and circumferential wave numbers in their study.

Knudsen number (Kn) is the dimensionless ratio that introduced mean free path of the fluid molecules to a characteristic length of the flow geometry and it is used as a discriminate for identifying the different flow regimes. Based on Kn values, four

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flow regimes may be identified: (a) $0\langle Kn \langle 10^{-2}$ for the continuum flow regime, (b) $10^{-2}\langle Kn \langle 10^{-1}$ for the slip flow regime, (c) $10^{-1} \langle Kn \langle 10$ for the transition flow regime, and (d) $Kn\rangle 10$ for the free molecular flow regime. Kn is larger than 10^{-2} for CNTs conveying fluids [8]. The effects of Knudsen-dependent nano flow velocity on vibrations of EB nano-pipe conveying fluid investigated by Mirramezani and Mirdamadi [8] and Rashidi et al. [9] who reformulated Navier–Stokes equations, with modified versions of Kn-dependent flow velocity. They found that the Knudsen number has dominated influence on the critical flow velocity and stability of nano structure conveying fluid.

Recently, it has become clear that when materials and structures shrink to nanometers, surface effects often play a critical role in their static or dynamical behavior due to increasing ratio of surface/inter face area to volume. Wang [10] presented an analytical model for predicting inner and outer layers effects on the free vibration of fluid-conveying nanotubes based on the nonlocal elasticity theory. They indicated that the surface effects with positive elastic constant or positive residual surface tension tend to increase the natural frequency and critical flow velocity. Also, Lei et al. [11] and Gheshlaghi and Hasheminejad [12] investigated the surface effects on the free vibration of nanotubes based on nonlocal Timoshenko beam (TB) and EB local beam, respectively.

In spite of many researches about behavior of CNTs using nonlocal elasticity theory, there are limited studies that consider nonlocal visco-elastic systems. Lei et al. [13] presented the dynamic behavior of nonlocal visco-elastic damped nanobeams where the Kelvin–Voigt visco-elastic model was employed to establish the governing equations for the bending vibration of nanotubes. They used transfer function method to obtain the natural frequencies and response functions. The flexural vibration of visco-elastic CNTs conveying fluid and embedded in viscous fluid based on TB elasticity theory investigated by Ghavanloo and Fazelzadeh [14] who demonstrated increasing visco-elastic structural damping coefficient decreases the critical flow velocity.

It has been proved that the CNTs deform when subjected to the magnetic field due to changes in their magnetic state.There are some studies dealing with on the magneto-elastic behavior of such components in the literatures. Murmu et al. [15] reported an analytical approach to study the effect of a longitudinal magnetic field on the transverse vibration of a magnetically sensitive DWCNT based on nonlocal elasticity theory. Results revealed that presence of a longitudinal magnetic field increases the natural frequencies of the DWCNT. They studied the influence of small scale effects, temperature change, Winkler constant and vibration modes of CNT on the natural frequency. Wang et al. [16] studied the effects of magnetic field and elastic medium on wave propagation in CNTs. They showed that the longitudinal magnetic field increases the velocity wave propagation in some frequency regions where the longitudinal magnetic field has obvious influence on the velocity of wave propagation in CNTs. The behavior of nanoplates under an external in-plane magnetic field based on nonlocal elasticity theory is investigated by Murmu et al. [17], who found that the in-plane magnetic field increases the natural frequencies of the single layer graphene sheet.

Murmu and Adhikari [18] investigated nonlocal vibration analysis of double nanobeam systems and obtained governing equations of motion for EBB model in terms of displacements. They solved its coupled equations by the new analytical method to decouple the set of partial differential equations and they showed that small scale parameters and stiffness of the coupling springs have important role in stability of double nanobeams system. Also these researchers [19,20] investigated the effects of small scale parameter on the transverse and longitudinal vibration of double nanobeams system. Later Murmu and Adhikari [21] reported nonlocal vibration of double nanoplate system. They used explicit closed-form expressions for natural frequencies for the case when all four ends are simply-supported. They showed the effect of stiffness elastic medium, small scale parameter, aspect ratio and higher modes on the natural frequencies of coupled system based on an analytical method. Recently, Ghorbanpour Arani and Amir [22] investigated electro-thermal vibration of double Boron Nitride nanotubes (BNNTs) which are coupled by elastic medium using strain gradient theory. Two BNNTs are placed in uniform temperature and electric fields, the latter being applied through attached electrodes at both ends. Moreover, one of the BNNTs oscillates under flow fluid. They derived the higher-order equations of motion base on the Hamilton's principle to obtain the frequency of coupled BNNTs system.

However, to date, no report has been found in the literature on the nonlocal visco-elastic vibration and instability response of conveying viscous fluid under magnetic field. Motivated by these considerations, in order to improve design of nano coupled system we aim to study the vibration analysis of double visco-CNTs system based on EBB theory under longitudinal magnetic field with surface effect. CNTs are conveying viscous fluid and coupled by visco-Pasternak medium. The DQ method is used to indicate the characteristic parameters of coupled visco-CNTs. The results of this study is hoped to be use to design this kind of nano devices.

2. The nonlocal elasticity model for CNT

Based on Eringen nonlocal elasticity model [23], the stress at a reference point x in a body is considered as a function of strains of all points in the near region. This assumption is agreement with experimental observations of atomic theory and lattice dynamics in phonon scattering in which for a homogeneous and isotropic elastic solid the partial nonlocality is:

$$\sigma(x) = E : \int_V \alpha(|x' - x|, \tau) dV(x'), \tag{1}$$

where symbols ':' is the inner product with double contraction, E is young's modulus, $\sigma(x)$ denotes the nonlocal stress tensor at x, and $\varepsilon(x')$ is the strain tensor at any point x' in the body. The kernel function $\alpha(|\,x' - x|, \tau)$ is the nonlocal modulus, $|x' - x|$ is the Euclidean distance, and $\tau = e_0 a/l$, where e_0 is constant suitable to each material, a is an interior features size and l is an external characteristic size. The volume integral in Eq. (1) is over the region V occupied by the body. The kernel function is given as [24]:

$$\alpha(|x|, \tau) = (2\pi l^2)^{-1} K_o\left(\frac{\sqrt{x.x}}{l\tau}\right) \tag{2}$$

where K_0 is the modified Bessel function. Combining Eqs. (1) and (2), the following equation can be written:

$$[1 - (e_0 a)^2 \nabla^2]\sigma = E : \varepsilon. \tag{3}$$

Fig. 1 shows double visco-elastic CNT which coupled by visco-Pasternak foundations with length l, radius r and effective tubes thickness h. Viscous fluid is conveying inner CNTs and the velocities of flow fluid in upper and lower tubes are U_f and $\Psi \times U_f$, respectively where Ψ demonstrates the ratio of velocity in lower tube to upper tube. CNTs are simulated EBB model where this simulation is suitable for CNTs, therefore the displacement filed based on the EBB theory becomes [6]:

$$\begin{aligned} \widetilde{U}(x,z,t) &= U(x,t) - z\frac{\partial W(x,t)}{\partial x}; \\ \widetilde{V}(x,z,t) &= 0 \\ \widetilde{W}(x,z,t) &= W(x,t). \end{aligned} \tag{4}$$