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Longitudinal vibration and stability analysis of carbon nanotubes conveying viscous fluid

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HIGHLIGHTS

- The results show that the axial vibrations of the nanotubesstrongly depend on the small-size effect.
- The fluid flowing in nanotube causes a decrease in the natural frequency of the system.
- The critical flow velocity decreases as the nonlocal parameter increases.

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ABSTRACT

Nowadays, carbon nanotubes (CNT) play an important role in practical applications in fluidic devices. To this end, researchers have studied various aspects of vibration analysis of a behavior of CNT conveying fluid. In this paper, based on nonlocal elasticity theory, single-walled carbon nanotube (SWCNT) is simulated. To investigate and analyze the effect of internal fluid flow on the longitudinal vibration and stability of SWCNT, the equation of motion for longitudinal vibration is obtained by using Navier-Stokes equations. In the governing equation of motion, the interaction of fluid-structure, dynamic and fluid flow velocity along the axial coordinate of the nanotube and the nano-scale effect of the structure are considered. To solve the nonlocal longitudinal vibration equation, the approximate Galerkin method is employed and appropriate simply supported boundary conditions are applied. The results show that the axial vibrations of the nanotubesstrongly depend on the small-size effect. In addition, the fluid flowing in nanotube causes a decrease in the natural frequency of the system. It is obvious that the system natural frequencies reach zero at lower critical flow velocities as the wave number increases. Moreover, the critical flow velocity decreases as the nonlocal parameter increases.

1. Introduction

Carbon is one of the wonderful elements in nature that is found in several solid types. Carbon atoms have been set systematically next to each other in their structures causing them to have remarkable properties, structures and behaviors. Extensive theoretical and experimental researches showed that they can be used in wide applications in nanotechnology, nano-biology as biological and molecular sensors, nano-electronics and nano-electromechanics (NEMS) as scanning molecule and ion conductance microscopy, nano-composites, nanofluidic-devices and other ranges of sciences as well as medical fields such as fluid storage, fluid transport and drug delivery. One of the subjects investigated for these practical applications is the dynamic behavior of CNT conveying fluid. In the nano-dimension, size and physical posture of nano-materials and manner of atomic bonds impress properties of materials. In addition, in the nano-scale, the motion of walled and fluid (internal or external), and their interaction that violently depends on size-scale, are of great importance. To measure and investigate the mechanical properties of CNTs, computational simulations are considered as strong and adequate methods. These methods include two main sets: molecular dynamic simulations (MD) and elastic continuum mechanics. In recent years, the continuum mechanic theories have attracted by researchers' attention for studying the mechanical behavior of CNT such as wave propagation, vibration and instability analysis. These continuum theories are of two forms, classical and non-classical. Classical continuum elasticity cannot predict the size-effect. For this reason, non-classical theories have usually been used in the theoretical researches of structures at small scales. There are various size

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dependent continuum theories such as surface stress theory, couple stress theory, strain gradient elasticity theory, strain/inertia gradient theory, modified couple stress theory and nonlocal elasticity (stress gradient) theory. The nonlocal continuum theory that overcomes the disadvantages of classical elasticity theory, was introduced for the first time by Eringen [1,2] in 1972. He introduced the nonlocal parameter; and by applying it, he was able to modify the classical continuum mechanics for taking the small-scale effects into account. Up to this time, many researchers in this field have investigated many aspects of vibration behavior with the mentioned theories. For example, Yoon et al. [4,5] studied the influence of internal flowing fluid on free vibration and flow-induced structural instabilities (divergence and flutter) of CNTs. They indicated that internal moving fluid has a substantial effect on vibrational frequencies especially for suspended, longer and larger-innermost-radius CNTs at higher flow velocity; and decaying rate of amplitude and the critical flow velocity for flutter instability in some cases may fall within the range of practical significance. Lee and Chang [6] used the nonlocal elastic model to analyze the free transverse vibration of the fluid-conveying SWCNT. They obtained that increasing the nonlocal effect decreased the real component of frequency, and that the mode shape was significantly influenced by the nonlocal parameter. Wang [7] investigated the surface effects on the vibration and stability of fluid-conveying nanotubes and nanopipes with inner and outer surface layers. He demonstrated that the surface elasticity and residual surface tension significantly affect the natural frequency and critical flow velocity of fluid-conveying nanotubes. Farshidianfar et al. [8] studied the free vibration and instability of fluid conveying SWCNTs by considering the effect of internal moving fluid, boundary conditions, elastic media and geometrical changes. In that paper, they observed that the divergence instability of SWCNT occurred at a certain critical velocity domain. Wang and Ni [9] reappraised the computational modeling of carbon nanotubes conveying viscous fluid, and reported that the effect of viscosity of fluid flow on the vibration and instability of CNTs could be ignored. Mirramezani and Mirdamadi [11] investigated the effect of viscosity of fluid flow in a channel, and the interaction between the fluid and structure. They reappraised the governing differential equation of pipe conveying viscous fluid and proposed that CNT conveying nano-fluid could remain more stable; furthermore, they observed that unlike the nonlocal continuum theory, the natural frequency predicted by the strain gradient theory is greater than that predicted by the classical continuum theory. Aydogdu [13] developed an elastic beam model and applied it to investigate the small-scale effect on axial vibration of nanorodes, and found that the axial vibration frequencies are highly overestimated by classical beam model because of ignoring the effect of small length scale. Murma and Adhikari [14] developed a nonlocal rod model for longitudinal vibration of double-nanorod-system (DNRS) based on Eringen's nonlocal continuum mechanics. They found that the longitudinal vibration frequencies of DNRS are overestimated by the classical nanorod model and that the stiffness of the coupling spring in DNRS has a subduing effect on the small-scale effects. Kiani [15] explored the free longitudinal vibration of tapered nanowires within the context of nonlocal theory of Eringen. He obtained that for nanowires with linearly varied radii, the proposed perturbation technique would be a suitable tool for analytically studying the free dynamic response of the nanowires with arbitrary varying radii. Nahvi and Basiri [16] investigated the axial vibration response of non-uniform nanorod by employing the nonlocal elasticity model. They found that the nonlocal vibration frequencies are smaller than the local ones for both uniform and tapered cross-section nanorods. Hu et al. [17] presented a brief review of vibrations of SWCNTs using the nonlocal beam, nonlocal rod and MD simulation. They reported that the nonlocal model can predict MD results better than classical model does for short SWCNTs, but the scale parameter in nonlocal model should be determined carefully for different situations, and also the MD results indicated that the classical beam and rod models can give good predictions of fundamental frequencies of long SWCNTs when the length is larger than 3.5 nm. Li et. al. [24] studied the nonlocal theoretical approaches and atomistic simulations for longitudinal free vibration of nanorods/nanotubes. They examine longitudinal dynamic behaviors of some common one-dimensional nanostructures (e.g. nanorods/nanotubes) using the hardening nonlocal approach. Their work proves that both the softening and hardening nonlocal models are correct in the dimensional numerical comparisons and It is concluded that the natural frequency for longitudinal free vibration is significantly influenced by the nonlocal nanoscale effect via a dimensionless parameter. Hosseini and Goughari [25] investigate the effect of a longitudinal magnetic field on the transverse vibration of a magnetically sensitive single-walled carbon nanotube (SWCNT) conveying fluid. Their results show that the fundamental natural frequency and critical flow velocity for the SWCNT increase as the nonlocal parameter increases, while in the presence of a strong longitudinal magnetic field the influence of internal fluid flow and nonlocal parameter on the vibrational frequencies of SWCNT can be reduced. Moreover, Zhang et al. [26] and Lei et al. [27] studies, respectively, the free vibration characteristics of functionally graded carbon nanotube-reinforced composite plates with elastically restrained edges and laminated plates with FG-CNTRC layers. Similar to linear vibration analysis, buckling of skew FG-CNTRC plates [28], postbuckling of FG CNTRC plates subjected to in-plane compressive loads [29]. Oveissi et al. [30] investigated the effects of small-scale of the both nano flow and nanostructure on the vibrational response of fluid flowing single-walled carbon nanotubes. They concluded that by increasing a non local parameter and Knudsen number the critical flow velocity decreases but it increases as the characteristic length related to the strain-inertia gradient theory increases.

In this paper, we applied some basic principles of fluid mechanics such as treatment of fluid with no-slip boundary condition and Navier-Stokes' equation, and reappraised the equation of motion of pipe flowing viscous fluid by using them. Moreover, we achieved a new equation for longitudinal vibrational behavior of carbon nanotubes conveying fluid flow by investigating the interaction of Fluid-Structure based on nonlocal elasticity theory of Eringen. To this end, the analysis way is used and the effects of internal fluid and size-scale of nanostructure on the longitudinal natural frequencies, mode shapes and instabilities of SWCNTs are studied.

2. A brief review of nonlocal theory of Eringen (stress gradient)

2.1. Nonlocal constitutive relations

According to Eringen [1,2], essential equations of nonlocal homogenous and isotropic linear elasticity, without considering body forces, can be written as:

$$\sigma_{ij,j} = 0$$
$$\sigma_{ij}(x) = \int \phi(|x - x'|, \tau) H_{ijkl} \varepsilon_{kl}(x') dv(x') \quad , \quad \forall x \in v$$
$$\varepsilon_{ij}(x') = \frac{1}{2}\left(\frac{\partial U_i(x')}{\partial x'_j} + \frac{\partial U_j(x')}{\partial x'_i}\right) \tag{1}$$

where σ_{ij}, ε_{ij} and H_{ijkl} are stress tensor, strain tensor and the fourth order elasticity modulus tensor on classical elasticity, respectively.