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Longitudinal vibration and instabilities of carbon nanotubes conveying fluid considering size effects of nanoflow and nanostructure

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HIGHLIGHTS

- The effects of small-scale of the both nanoflow and nanostructure on the vibrational response of fluid flowing single-walled carbon nanotubes are investigated.
- Critical flow velocity decreases as the wave number increases, employed.
- *Kn* effect has considerable impact on the reduction of critical velocities especially for the air-flow flowing through the CNT.

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ABSTRACT

In this study, the effects of small-scale of the both nanoflow and nanostructure on the vibrational response of fluid flowing single-walled carbon nanotubes are investigated. To this purpose, two various flowing fluids, the air-nano-flow and the water nano-flow using Knudsen number, and two different continuum theories, the nonlocal theory and the strain-inertia gradient theory are studied. Nano-rod model is used to model the fluid-structure interaction, and Galerkin method of weighted residual is utilizing to solve and discretize the governing obtained equations. It is found that the critical flow velocity decreases as the wave number increases, excluding the first mode divergence that it has the least value among of the other instabilities if the strain-inertia gradient theory is employed. Moreover, it is observed that *Kn* effect has considerable impact on the reduction of critical velocities especially for the air-flow flowing through the CNT. In addition, by increasing a nonlocal parameter and Knudsen number the critical flow velocity decreases but it increases as the characteristic length related to the strain-inertia gradient theory increases.

1. Introduction

Due to ongoing development of the science and technology, the humankind requirements become different, and to satisfy not only routine needs but also inborn curiosity to know, many researches are done about unknowns. One of those is the plenty of rooms that exist at the bottom, Feynman said [1]. Today, many scientist interested in nanotechnology field, and chiefly carbon nanotubes discovered by Iijima [2] in 1991. Just one of the astonishing properties of CNTs is their mechanical behavior because of their high strength, geometrical structure, low mass density and linear elastic behavior. Nano-fluidic devices are from the subjects that they are studied by researchers in this field such as fluid storage, fluid transport and drug delivery [3,4]. To this end, the dynamic behavior of CNT conveying fluid should be investigated. For example, Lee and Chang [5] investigated the effect of small-size on the equations of motion using nonlocal elasticity. They found that the combination of the first and the second modes appeared above the critical flow velocity. Wang et al. [6] studied the wave propagation characteristics in nanotubes conveying viscous fluid based on the nonlocal continuum theory. They reported that with different fluid viscosities, the dispersion relation is almost the same for small wave number; but for larger wave number, the wave frequency becomes higher by increasing the fluid viscosity. Rashidi et al. [7] presented one model for a single mode of coupled vibration of fluid conveying CNTs considering the slip boundary conditions of nanoflow. They expressed that the critical flow velocities could decrease if the passage fluid is a gas with nonzero *Kn*, in comparison with a liquid nanoflow. Ghavanloo and Fazelzadeh [8] investigated the vibration characteristics of nanotubes embedded in viscous fluid by the Timoshenko beam model

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with the nonlocal thermal elastic theory and they discussed effects of both the internal and external fluid. They revealed that the critical velocity could be reduced by the external fluid. Moreover, recent researchers found that the dynamical coupling of the liquid flow and electron transport in the structure of water-filled nanotube could generate voltage, which allowed the application of the flow sensor and energy harvesting at the nano scale [9,10].

The above-mentioned researches and another same works, often studied about transverse vibration response of CNTs conveying fluid. Axial vibration behavior of nanorod is investigated by Aydogdu [11]. He developed and applied an elastic beam models to investigate the small-scale effect on axial vibration of nanorods based on local and nonlocal rod theories. He found that the axial vibration frequencies are highly overestimated by the classical (local) beam model because of ignoring the effect of small length scale. Aydogdu [12] developed longitudinal wave propagation for Elastic multi-walled local and nonlocal rod models. He considers the effect of the van der Waals force in the axial direction and demonstrates the possibility of relative displacement between nanotubes. Murma and Adhikari [13] developed a nonlocal rod model for longitudinal vibration of double-nanorod-system (DNRS) based on Eringen's nonlocal continuum mechanics. They found that the classical nanorod model overestimates the longitudinal vibration frequencies of DNRS and the stiffness of the coupling spring in DNRS has a subduing effect on the small-scale effects. Hu et al. [14] presented a brief review of vibrations of SWCNTs using the nonlocal beam, nonlocal rod and molecular dynamic (MD) simulation. They reported that the nonlocal model can predict MD results better than the classical model does for short SWCNTs, 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. [21] investigated the nonlocal theoretical approaches and atomistic simulations for longitudinal free vibration of nanorods/nanotubes and verification of different nonlocal models. They provide a comparative calculation for dimensional natural frequencies with respect to length of CNTs by different methodologies to explain why the softening and hardening nonlocal models are both correct in nonlocal elasticity theory. The free vibration of embedded single-walled fluid-conveying carbon nanotubes in magnetic and temperature fields is investigated by Wang et al. [22]. They reported that the fluid flowing inside the nanotubes can make the tubes more flexible. The frequencies and critical flow velocity are much influenced by temperature change, magnetic flux and Pasternak-type foundation, which can make fluid-conveying wavy SWCNTs stiffer. Guo and Zhang [23] studied the nonlinear vibration behaviors of a reinforced composite plate with the carbon nanotubes under combined the parametric and forcing excitations using the Mori–Tanaka method and the method of calculating the average stress of composite materials. Fereidoon et al. [24] studies the nonlinear vibration of viscoelastic embedded nano-sandwich structures containing of a double walled carbon nanotube (DWCNT) integrated with two piezoelectric Zinc oxide (ZnO) layers. They indicate that the frequency and critical velocity increases with assume of surface effects.

In this study, based on the nanorod model and by using some basic principles of the fluid mechanics, the governing equation of motion related to the longitudinal vibration response of carbon nanotubes conveying viscous fluid is investigated. In order to indicate the small-scale effects of the nanostructure, two continuum theories, the nonlocal theory and the strain-inertia gradient theory are used. To show the small-size effect of the nanoflow, Knudsen number is considered both gas and liquid flowing through CNT and then the results are compared. The vibration analysis of the system and discretization of the equations of motion are accomplished by utilizing the Galerkin approximate method. The first three frequencies and critical flow velocities for each fluid are determined for two simply supported ends CNT conveying fluid. The effects of the nonlocal parameter, characteristic lengths related to the strain-inertia gradient theory and Knudsen number are elucidated on the natural frequencies and critical flow velocities.

2. The governing equations of motion for fluid flow-conveying CNTs

2.1. The equation of motion of the pipe

According to the Newton's second law, one knows:

$$\sum F_{ext} + \sum F_{\text{int}} = m_c \frac{\partial^2 U}{\partial t^2} \tag{1}$$

where the first and second terms on the left hand side are the sum of the external and internal forces acting on the tube at the x direction, respectively; m_c is the mass per unit length; t, time and U is the longitudinal displacement of the CNT wall.

The internal forces follow from the equilibrium equation are:

$$\sum F_{\text{int}} = \frac{\partial N}{\partial x} + f_{bx} \tag{2}$$

where f_{bx} is the body force acting on the x direction such as the magnetic field force and et cetera that, they are being ignored in here and N is the axial internal force as:

$$N = \int_A \sigma_{xx} dA \tag{3}$$

Therefore, Eq. (1) can be rewritten as:

$$\sum F_{ext} + \frac{\partial N}{\partial x} = m_c \frac{\partial^2 U}{\partial t^2} \tag{4}$$

2.2. The fluid's behavior on the axial direction

According to the Navier-Stokes's equation, we have:

$$\rho \frac{D\vec{V}}{Dt} = -\nabla\vec{P} + \mu\nabla^2\vec{V} + \vec{F}_{body} \tag{5}$$

where $D\vec{V}/Dt$ is the material derivative; $\rho, \vec{V}$ and $\vec{P}$ are the mass density, the flow velocity and the pressure of the flowing fluid, respectively; $\vec{F}_{body}$ represent the body forces acting on the fluid; ∇ and ∇^2 are the gradient and the Laplace operators, respectively. The fluid flow is considered incompressible, Newtonian, laminar, infinite, uniform flow and viscous.

The differential form of the equation of conservation momentum as an equilibrium equation for each fluid element at the axial direction can be written as:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{zx}}{\partial x} + \rho f_{body} = \rho a_x \tag{6}$$

in which the normal stress σ_x, following the continuity principle is [15]:

$$\sigma_x = -p + 2\mu \frac{\partial u}{\partial x} \tag{7}$$

where u is the velocity of the fluid flow in the longitudinal direction on the CNT wall.

According to the definition of the material derivative in the lagrangian system, replaced it by the acceleration of the fluid element on the right hand side of Eq. (6); by substituting Eq. (7) into Eq. (6) and equating the flow velocity in the y and z direction