Computational Materials Science 77 (2013) 161–171

Contents lists available at SciVerse ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Innovative coupled fluid–structure interaction model for carbon nano-tubes conveying fluid by considering the size effects of nano-flow and nano-structure

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ARTICLE INFO

Article history:
Received 20 February 2013
Received in revised form 8 April 2013
Accepted 16 April 2013
Available online 18 May 2013

Keywords:
Fluid–structure interaction (FSI)
Divergence instability
Critical flow velocity
Knudsen number
Viscosity parameter
Size-dependent continuum theory

ABSTRACT

In this article, we reappraise the well-known equation of motion for a pipe conveying viscous fluid. We utilize prominent principles of fluid mechanics such as Navier–Stokes' equation as well as several benchmark references in the field of fluid–structure interaction (FSI) to reveal that the viscosity of the fluid flow should not appear explicitly in the equation of motion of pipe conveying fluid. Based on this result, we could develop an innovative model for one dimensional coupled vibrations of carbon nano-tubes (CNTs) conveying fluid using slip velocity of the fluid flow on the CNT walls as well as utilizing size-dependent continuum theories to consider the size effects of nano-flow and nano-structure. Therefore, this innovative coupled FSI equation suggests that CNTs conveying nano-flow remain stable for higher velocities. In the other words, the critical average velocity of the fluid flow at which the divergence instability occurs, should be greater in comparison with the critical velocity predicted by the models used plug flow and classical continuum theories.

1. Introduction

Carbon nano-tubes (CNTs) are becoming the most promising material for nano-electronics, nano-devices and nano-composites because of their enormous application such as nano-pipettes, actuators, reactors, fluid filtration devices, biomimetic selective transport of ions, targeted drug delivery devices, scanning molecule microscopy, and scanning ion conductance microscopy [1–4]. In this regard, a remarkable number of studies have been accomplished to disclose the vibrational behavior of such nano-structures conveying fluid. Tuzun et al. [5], Amabili et al. [6], Yoon et al. [7], Natsuki et al. [8], Wang et al. [9], Xia et al. [10] and Wang and Qiao [11] made important contributions in this practical area. In this research, we would undertake a reevaluation for computational modeling of carbon nano-tubes conveying viscous fluid with some fresh insights as well as we try to develop an innovative one dimensional (1D) coupled fluid–structure interaction (FSI) equation by considering slip condition on the nano-tube wall. Khosravian and Rafii Tabar [12] studied the flow of viscous fluid through a carbon nano-tube and established a new equation of motion of pipe conveying fluid by considering the viscosity effect. They found that a nano-tube conveying a viscous fluid was more stable against vibration-induced buckling than a nano-tube conveying a non-viscous fluid. Wang and Ni [13] reappraised the computational modeling of carbon nano-tube conveying viscous fluid represented by Khosravian and Rafii Tabar [12] and then corrected the FSI equation and disclosed that the effect of viscosity of fluid flow on the vibration and instability of CNTs could be ignored. Lee and Chang [14] analyzed the influences of nonlocal effect, viscosity effect, aspect ratio, and elastic medium constant on the fundamental frequency of a single-walled carbon nano-tube (SWCNT) conveying viscous fluid embedded in an elastic medium. They revealed that the frequency increased as the values of the viscosity parameter increased. Soltani et al. [15] developed a transverse vibrational model for a viscous fluid-conveying SWCNT embedded in biological soft tissue. Their investigation determined that the structural instability and the associated critical flow velocity could be affected by the viscosity of the fluid and the nonlocal parameter. Khoddami et al. [16] studied electro-thermo nonlinear vibration and instability of embedded double-walled Boron Nitride nano-tubes (DWBNNTs) conveying viscous fluid based on nonlocal piezoelasticity theory. They reported that increasing the small scale parameter decreased the real and imaginary parts of frequency and critical fluid velocity. Furthermore, they concluded that the effect of fluid viscosity on the vibration and instability of DWBNNTs might be ignored. In many recent studies various size-dependent continuum theories have been developed for vibration and stability analysis of CNTs conveying fluid. Lee and Chang [17], Zhen

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http://dx.doi.org/10.1016/j.commatsci.2013.04.047

and Fang [18], Jannesari et al. [19] included the effect of small-size into equations of motion by using nonlocal elasticity in their studies and showed that increasing nonlocal parameter had the effect of a decrease in the critical velocity of fluid. Ke and Wang [20] investigated vibration and instability of fluid-conveying double-walled carbon nano-tubes based on modified couple stress theory. They showed that the imaginary component of the frequency and the critical flow velocity of the CNTs increased with an increase in length scale parameter. Wang [21] developed a theoretical analysis of wave propagation of fluid-conveying single-walled carbon nanotubes based on strain gradient elasticity theory. He showed that the use of gradient elasticity theory had a dramatic effect on dispersion relation. Wang [22] utilized nonlocal elasticity theory integrated with surface elasticity theory to analyze dynamic response of nano-tubes conveying fluid. He revealed that fundamental frequency and critical flow velocity predicted by his new model was generally higher than that predicted by the Euler–Bernoulli beam model without surface effects. Some recent studies developed to consider the small size effects of nano-flow as well as slip boundary condition on nano-tube wall. For instance, Rashidi et al. [23] presented an original model for a single-mode coupled vibrations of nano-tubes conveying fluid by considering the slip boundary conditions of nano-flow quantified by Knudsen number (*Kn*). They reported, for the passage of gas through a nano-pipe with nonzero *Kn*, that the critical flow velocities could decrease considerably in comparison with a liquid nano-flow. Mirramezani and Mirdamadi [24] investigated coupled-mode flutter stability of nano-tube conveying gas and liquid nano-flow for different beam boundary conditions and multi-mode analysis. They observed that coupled-mode flutter might occur much sooner by considering slip condition than that predicted by continuum theory. Kaviani and Mirdamadi [25] studied the wave propagation phenomena in CNT conveying fluid. The CNT structure was modeled by using size-dependent strain/inertia gradient theory of continuum mechanics, the CNT wall-fluid interaction by slip boundary condition and Knudsen number (*Kn*). They reported that *Kn* could impress complex wave frequencies at both lower and higher ranges of wave numbers, while the small-size had impression at the higher range. Mirramezani and Mirdamadi [26] investigated the effect of nano-size of both fluid flow and elastic structure simultaneously on the vibrational behavior of a nano-tube conveying fluid using both *Kn* and nonlocal continuum theory. It was observed that the nonlocal parameter would have more effect than *Kn* on the reduction of critical velocities of a liquid nano-flow. This effect had considerable impact on the reduction of critical velocities for a clamped–clamped beam in comparison with a pinned–pinned one. Kaviani and Mirdamadi [27] considered the coupled effects of *Kn* and slip boundary condition on the viscosity of a nano-flow passing through a nano-tube. *Kn*-dependent viscosity could affect both directly on viscosity values and indirectly on a dimensionless parameter, velocity correction factor, VCF, defined as the ratio of no-slip flow velocity to slip flow velocity on the boundaries of a nano-tube. They concluded that the effect of viscosity on the critical flow velocity could be so large that for a specific numerical study could reach one-fourth of that velocity, by ignoring the viscosity effect on slip boundary condition. Matin et al. [28] studied the effects of nonlocal elasticity and slip condition on vibration of nano-plate coupled with fluid flow. They reported that the effect of nonlocal parameter would be considerable for plate lengths less than 50 nm as well as when the fluid is a liquid, most of the contribution in decreasing critical flow velocity is due to nonlocal parameter but when the fluid is a gas, *Kn* has a greater role in decreasing the critical velocity.

A partial objective of this study is to reappraise the equation of motion of pipe conveying viscous fluid extracted by Khosravian and Rafii Tabar [12]. In this article, we utilize basic principles of fluid mechanics such as Navier–Stokes' equation; moreover, we benefit from some valuable classical works in the field of FSI to reveal that the viscosity of the fluid flow should not appear explicitly in the equation of motion. Furthermore, we propose a novel model, for 1D coupled vibrations of carbon nano-tubes (CNTs) conveying fluid, taking into account the slip boundary condition using Knudsen number as well as size-dependent continuum theories such as strain/inertia gradient and nonlocal theories. It could be seen that the current model by considering the size effects of nano-flow and nano-structure, the critical mean flow velocity at which the divergence-type instability might occur, could differ remarkably from that of a plug flow model for the fluid flow.

The remainder of this study is organized as follows: In Section 2, we reappraise the equation of motion of pipe conveying viscous fluid. In Section 3, we develop an innovative 1D coupled FSI equation by considering slip condition and size-dependent continuum theories. In Section 4, we implement the Galerkin weighted-residual solution technique and solve the partial differential equations of nano-tube vibrations. In Section 5, we discuss stability analysis and present the results. Finally, in Section 6, we express our conclusions.

2. Reappraise the equation of motion of pipe conveying viscous fluid

The flexural vibrations of an Euler–Bernoulli beam subjected to an external force can be modeled via the following equation [29]:

$$-\frac{\partial^2 M}{\partial x^2} + m_c \frac{\partial^2 W}{\partial t^2} = F_{ext} \tag{1}$$

where x is the longitudinal coordinate of tube elastic axis; m_c, the CNT mass per unit length; W is the flexural displacement of the CNT wall; t, time; F_{ext} is the transversal external force acting on the beam due to the flowing fluid and M is the bending moment. The bending moment for an Euler–Bernoulli beam is given by:

$$M = -EI \frac{\partial^2 W}{\partial x^2} \tag{2}$$

where E is Young's modulus and I is the moment of inertia of area cross section. In the following part of this section, we benefit from the well-known Navier–Stokes' equation to compute the F_{ext} exerted by the fluid flow on the wall of CNT conveying viscous fluid.

2.1. A brief review on fluid mechanics

We consider an incompressible, laminar, infinite and viscous fluid flowing through the CNT. The momentum-balance equation for the fluid motion may be described by the well-known Navier–Stokes' equation as [30]:

$$\rho \frac{D\vec{V}}{Dt} = -\nabla \vec{P} + \mu \nabla^2 \vec{V} + \vec{F}_{body} \tag{3}$$

where D/Dt is the material or total derivative and $\vec{V}$ is the flow velocity, $\vec{P}$ and μ are, respectively, the pressure and the viscosity of the flowing fluid, ρ is the mass density of the internal fluid, and $\vec{F}_{body}$ represents body forces. The body forces are due to external fields like gravity, magnetism an electric potential, which would act upon the entire mass within the body. We neglect these effects and ignore the body forces. In the following equations, we concentrate on how to compute the F_{ext} exerted by the fluid flow on the wall of CNT conveying viscous fluid using basic principles of fluid mechanics to modify the equation of motion extracted by Refs. [12,13]. According to the reference [30] the total force exerted on the differential element of the fluid in each direction can be com-