International Journal of Engineering Science 87 (2015) 13–22

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

On nonlinear behavior and buckling of fluid-transporting nanotubes

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ARTICLE INFO

Article history:
Received 21 August 2014
Received in revised form 22 October 2014
Accepted 1 November 2014
Available online 21 November 2014

Keywords:
Nanotube conveying fluid
Nonlinear model
Nonlocal elasticity theory
Post-buckling
Natural frequency

ABSTRACT

A general nonlinear nonlocal model for supported nanotubes conveying fluid is developed. Considering the geometric nonlinearity associated with the mid-plane stretching of the nanotube, the extended Hamilton's principle is used to derive this general model based on Eringen's nonlocal elasticity theory. Analytical solutions for the nonlinear responses of the nanotube are obtained from the constructed nonlinear equation. It is shown that the presence of the nonlocal effect tends to decrease the critical flow velocity and increase the buckled static displacement of the nanotube. It is also demonstrated that the nonlocal effect has a significant impact on the pre- and post-buckling natural frequencies of the nanotube while the mass ratio mainly influences the post-buckling frequencies and the geometric nonlinearity term has no effect on these frequencies of the nanotube.

1. Introduction

In the past two decades, hollow nanobeams, also known as nanotubes or nanopipes, have been reported to be a class of new nano-fluidic devices and systems. One of the attractive features of such structures is the ability of transporting liquid-like materials (e.g., water, cells, and nanoparticles). For this reason, hollow nanobeams are also expected to have the potential for nanopipettes, fluid filtration devices, targeted drug delivery devices, biomimetic selective transport of ions, fountain pen nanochemistry for chromium etching, etc. (Longhurst & Quirke, 2007; Wang, 2005, 2009).

In the past years, a number of theoretical studies have been focused on understanding the responses of fluid-loaded nanotubes/microtubes (Dai, Wang, & Ni, 2014; Ke & Wang, 2010; Kuang, He, Chen, & Li, 2009; Lee & Chang, 2008; Liang & Su, 2013; Tang, Ni, Wang, Luo, & Wang, 2014; Wang, Guo, & Hu, 2009; Wang, Liu, Ni, & Wu, 2013; Wang & Ni, 2008; Yan, Wang, & Zhang, 2010; Yang, Jia, Yang, & Fang, 2014; Yoon, Ru, & Mioduchowski, 2006). The earliest research studies of the vibrations of fluid-conveying nanotubes were based on linear analyses without considering possible nonlinear sources. To determine the linear governing equations of these fluid-loaded nanotubes, both classical continuum models (Yoon et al., 2006) and non-classical continuum models (Ke & Wang, 2010; Kuang et al., 2009; Lee & Chang, 2008) have been developed. It was demonstrated that a cantilevered nanotube conveying fluid may lose stability via flutter at very high flow velocities

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http://dx.doi.org/10.1016/j.ijengsci.2014.11.005
0020-7225/

(Yoon et al., 2006). On the other hand, for supported nanotubes conveying fluid, it was found that the possible form of instability is buckling (Lee & Chang, 2008), i.e. the original equilibrium point becomes statically unstable.

However, some key questions associated with the dynamical behaviors of supported nanotubes conveying fluid cannot be answered except by nonlinear theory. For example, using the linear equation of motion, it is impossible to determine the responses of the system when the flow velocity is beyond the critical value. Also, the existence of post-divergence flutter predicted by linear theory (Wang, 2009) is questionable and has to be reassessed by nonlinear theory. Because the original equilibrium has become unstable after buckling, motions would actually take place about a new equilibrium position. These and other questions are some of the aspects on this topic and should be tackled by performing nonlinear analyses.

The literature on nonlinear behaviors of nanotubes conveying fluid is relatively limited. Kuang et al. (2009) studied the effects of geometric nonlinearity and another nonlinearity arising from van der Waals (vdW) forces on the transverse vibration of double-walled carbon nanotubes (DWCNTs) conveying fluid. Rasekh and Khadem (2009) developed a nonlinear vibration model for a fluid-conveying single-walled carbon nanotube (SWCNT) embedded in a Winkler-type elastic foundation. However, in these two mentioned studies, the nonlinear governing equations of motion were derived based on the classical continuum theory. Using Newton's law, Soltani and Farshidianfar (2012) derived the nonlinear equation of lateral motion of a SWCNT conveying fluid based on Eringen's nonlocal elasticity theory. It was shown that the effect of nonlocal parameter on the nonlinear frequency is not pronounced. Based on the Hamilton's principle, Farshidianfar and Soltani (2012) also derived the equation of motion for this problem. However, the nonlinear responses when the CNTs are buckled were not analyzed. Ali-Asgari, Mirdamadi, and Ghayour (2013) studied the natural frequency and responses of CNTs conveying fluid based on the coupling of nonlocal theory and von Karman's stretching. Arani and his co-authors (Arani & Kolahchi, 2014; Arani, Kolahchi, Haghighi, & Barzoki, 2013; Arani, Bagheri, Kolahchi, & Maraghi, 2013; Arani, Hashemiana, & Kolahchia, 2013) have done a lot of work on the nonlinear vibrations and instability of fluid-conveying boron nitride nanotubes (BNNTs) and carbon nanocones (CNCs). The nonlinear frequencies and critical flow velocity of the BNNTs and CNCs have been investigated. Arani, Shajaria, Amira, and Loghmana (2012) and Arani, Shajaria, Atabakhshiana, Amira, and Loghmana (2013) also studied the nonlinear frequency and stability of smart composite microtubes made of Poly-vinylidene fluoride (PVDF) reinforced by Boron-Nitride nanotubes (BNNTs) with consideration of the effects of internal fluid flow, imposed electric potential, small scale, volume percent, and orientation angle of the BNNTs. The smart microtube was modeled as either a thin shell (Arani et al., 2012) based on the nonlinear Donnell's shell theory or an Euler–Bernoulli beam (Arani et al., 2013).

It is noted that all the research studies mentioned in the foregoing have not paid attention to the post-buckling responses of nanotubes conveying fluid. Recently, Ghasemi, Dardel, Ghasemi, and Barzegari (2013) discussed the buckling and post-buckling of fluid-conveying multi-walled carbon nanotubes (MWCNTs). The nonlinear governing equations and boundary conditions were derived based on Eringen's nonlocal elasticity theory. However, their nonlinear governing equations have no time-dependent terms and hence are only suitable for static analysis of nanotubes conveying fluid.

From the literature discussed above, it is found that most investigations on the nonlinear behaviors of nanotubes conveying fluid were limited to "specific" nanotubes, such as CNTs, BNNTs and CNCs. There is still lack of unified or general theoretical models for predicting the nonlinear responses of "generic" nanotubes conveying fluid. Consequently, the post-buckling dynamics of fluid-conveying nanotubes has not been well understood yet. This motivates the current work.

In the present work, we aim to develop a general nonlocal nonlinear Euler–Bernoulli beam model for dynamic analysis of simply-supported nanotubes conveying fluid. In particular, the nonlinear equation of motion, from which the dynamical behaviors of the system can be predicted, is derived based on the extended Hamilton's principle and the nonlocal elasticity theory which is presented in Section 2. Since a nonlocal nanoscale parameter has been introduced in this nonlinear model, the nonlinear equation of motion enables us to analyze the size effect on the transverse motion. In Section 3, the post-buckling configurations of the nanotubes conveying fluid are obtained analytically, showing the essential details of dynamic responses of the system when the flow velocity is beyond the critical value. Furthermore, the size effect on the first two natural frequencies of the nanotube under pre- and post-buckling conditions has been investigated in Section 4. Summary and conclusions are presented in Section 5.

2. Mathematical modeling

The system under consideration is composed of a uniform nanotube with internal fluid flow, as shown in Fig. 1. The nanotube is simply-supported at both ends with x, t and $w(x, t)$ showing the axial, time coordinates, and the transverse displacement, respectively. The length, elasticity modulus, mass per unit length, and cross-section area of the nanotube are denoted, respectively, by L, E, m, and A.

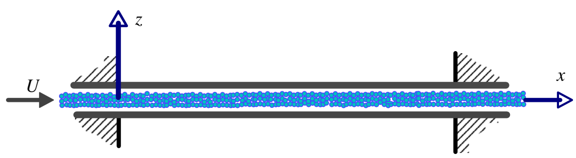

Fig. 1. Schematic of a nanotube containing internal fluid flow.