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Nonlinear mechanics of nanotubes conveying fluid

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ABSTRACT

A nonlocal strain gradient elasticity approach is proposed for the mechanical behaviour of fluid-conveying nanotubes; a nonlinear analysis, incorporating stretching, is conducted for a model based on both a nonlocal theory along with a strain gradient one. A clamped–clamped nanotube conveying fluid, as a conservative gyroscopic nanosystem, is considered and the motion energy and size-dependent potential energy are developed via use of constitutive and strain–displacement relations. An energy minimisation is conducted via Hamilton's method for an oscillating nanotube subject to external forces. This gives the nonlinear equation of the motion which is reduced to a high DOF system via Galerkin's technique. As many nanodevices operate near resonance, the resonant motions are obtained using a frequency-continuation method. The effect of different nanosystem/fluid parameters, including fluid/solid interface and the flow speed, on the nonlinear resonance is analysed.

1. Introduction

Mechanical analysis of Micro/Nanoelectromechanical systems (MEMS/NEMS) (Ghayesh & Farokhi, 2015; Ghayesh, Amabili, & Farokhi, 2013; Ghayesh, Farokhi, & Gholipour, 2017) is an area of research that has received a great deal of attention recently (Farokhi & Ghayesh, 2018; Farokhi, Ghayesh, & Amabili, 2013; Ghayesh, Farokhi, & Alici, 2016; Ghayesh, Farokhi, & Amabili, 2013a; Mojahedi, 2017; Qi, Huang, Fu, Zhou, & Jiang, 2018). In some promising nanoelectromechanical systems (NEMSs), there is significant interaction between the solid parts and the liquid ones. A salient example of these NEMS devices is nanofluidics-based systems which have a wide range of applications in different areas of nanotechnology, especially nanomedicine. To have a better performance for fluid-conveying nanostructures understanding the effects of fluid-solid interactions on the mechanical response such as dynamic response is important for an appropriate design since these nanostructures usually operate under applied loads. Size dependence (Attia & Abdel Rahman, 2018; Bahaadini, Saidi, & Hosseini, 2018; Barretta, Čanađija, Luciano, & de Sciarra, 2018; Dehrouyeh-Semnani, 2018; Ghayesh & Farajpour, 2018; Ghayesh & Farokhi, 2018; Ghayesh, Farokhi, & Amabili, 2013b; Ghayesh, Farokhi, Gholipour, & Tavallaeinejad, 2018; Hadi, Nejad, & Hosseini, 2018; Khaniki, 2018; Li, Tang & Hu, 2018; Srividhya, Raghu, Rajagopal, & Reddy, 2018; Taati, 2018) is an important factor to be incorporated in the theoretical modelling and simulations of MEMS/NEMS applications

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(Attia, 2017; Bakhshi Khaniki & Hosseini-Hashemi, 2017; Dehrouyeh-Semnani, 2017; Dehrouyeh-Semnani, Nikkhah-Bahrami, & Yazdi, 2017; Demir & Civalek, 2017; Farokhi, Ghayesh & Gholipour, 2017; Farokhi, Ghayesh, Gholipour, & Hussain, 2017; Farokhi, Ghayesh, Gholipour, & Tavallaeinejad, 2017a, 2017b; Ghayesh & Farokhi, 2017a, 2017; Ghayesh, Farokhi, & Gholipour, 2017; Ghayesh, Farokhi, Gholipour & Hussain, 2017; Ghayesh, Farokhi, Gholipour, & Tavallaeinejad, 2017; Medina, Gilat, & Krylov, 2017; Rahaeifard & Mojahedi, 2017; Rajasekaran & Khaniki, 2017; Seyedkavoosi et al., 2017; Shahverdi & Barati, 2017a, 2017; She, Yuan, Ren, & Xiao, 2017; Xu, Zheng, & Wang, 2017).

Some size-dependent mathematical formulation has been recently developed in order to study the mechanics of fluid-conveying nanostructures using various modified elasticity models such as the couple stress (Ghayesh, Farokhi, & Hussain, 2016; Ma, Gao, & Reddy, 2008), nonlocal elasticity (Aydogdu & Elishakoff, 2014; Farajpour, Shahidi, Tabataba'i-Nasab, & Farajpour, 2018) and surface elasticity (Malekzadeh & Shojaee, 2013). Wang (2010) investigated the vibration of nanoscale tubes containing flowing fluid via a mathematical surface model. Lee and Chang (2008) developed a nonlocal model to study the time-dependent deformation of single-walled carbon nanotubes (SWCNTs) conveying fluid; they only considered linear terms in their analysis. Wang, Li, and Kishimoto (2010) also examined the features of wave propagations in a double-walled nanoscale tube containing flowing fluid. In another paper, Soltani, Taherian, and Farshidianfar (2010) examined the effect of stress nonlocality on the instability of a viscous-fluid-conveying SWCNT surrounded by a viscoelastic medium. Zeighampour and Beni (2014) proposed a couple stress model to explore the vibration of fluid-conveying nanotubes; they studied vibration characteristics due to small time-dependent deflections. In another study, thermal effects on the stability responses of fluid-conveying nanoscale tubes were investigated by Zhen, Fang, and Tang (2011). Moreover, Maraghi, Arani, Kolahchi, Amir, and Bagheri (2013) employed the nonlocal Euler–Bernoulli beam theory to describe the thermo-electro-mechanical nonlinear mechanics of double-walled boron nitride nanoscale tubes conveying fluid. Liang and Su (2013) also developed a nonlocal continuum formulation for the stability of a SWCNT conveying pulsating fluid; the effect of being small was ignored for the nanoscale fluid. In another paper, a nonlinear analysis was performed by Askari and Esmailzadeh (2017) to study the large amplitude vibration of fluid conveying nanotubes; only one scale parameter was considered to describe the size effects. Oveissi, Toghraie, and Eftekhari (2016) also studied the axial vibration of nanoscale tubes conveying fluid using the nonlocal theory. Ghasemi, Dardel, Ghasemi, and Barzegari (2013) performed an analytical analysis to examine the post-buckling behaviour of multi-walled carbon nanotubes containing flowing fluid; they employed a nonlocal continuum mechanics for size effects. The effect of an applied magnetic field on the nonlocal instability of fluid-conveying nanotubes was also studied by Bahaadini and Hosseini (2016). More recently, a linear wave propagation analysis has been reported on the vibration of viscoelastic nanotubes including fluid-solid interactions (Li & Hu, 2016).

The class of nanotubes conveying fluid is gyroscopic and conservative/non-conservative; a clamped–clamped one considered in this paper is conservative gyroscopic (in the absence of viscosity), meaning that both Coriolis and centrifugal forces are present, the former due to rotations and relative translations, and the latter one due to a curvature and relative fluid translation.

All the above-explained investigations are restricted to either linear models or simple one-parameter size-dependent models. In this paper, for the first time, a nonlinear nonlocal strain gradient technique is presented for a viscoelastic nanotube conveying fluid. Both the effects of nonlocal stresses and the strain gradient are incorporated. The ends of the nanotube are assumed to be clamped, leading to a gyroscopic nanosystem. Using modified constitutive equations and strain–displacement relations, the motion energy and the size-dependent potential energy are developed. Then an energy minimisation is performed by Hamilton's method, giving the nonlinear equation of the size-dependent motion. As a decomposition approach, Galerkin's procedure is applied to the derived equation. The resonant response of the fluid-conveying nanotube is determined via a frequency-continuation method. At the end, the influences of various nanotube/nanofluid parameters such as the scale parameters and the speed of the flowing fluid on the nonlinear response are studied.

2. Effect of slip boundary condition

At macroscale levels, it is usually assumed that the no-slip boundary condition is valid at the interface between the tube and the fluid of a system containing flowing fluid. However, when the dimensions of a system are reduced to nanometres, the no-slip boundary condition is not valid anymore. To take into account the effect of slip boundary conditions, a non-dimensional parameter termed Knudsen number (Kn) is defined as the ratio of the average distance of the molecular free path to an external characteristics dimension of a fluid-conveying system. Using this parameter, the effective viscosity of the fluid (μ_{nf}) can be defined as (Beskok & Karniadakis, 1999)

$$\mu_{nf} = \frac{\mu_{nf0}}{1 + \lambda Kn}, \tag{1}$$

where μ_{nf0} denotes the bulk viscosity. λ is a constant coefficient obtained by

$$\lambda = \frac{2\lambda_0}{\pi}\tan^{-1}\left[\alpha_0 (Kn)^{\alpha_1}\right], \tag{2}$$

where

$$\lambda_0 = \lim_{Kn\to\infty} \lambda = \frac{64\beta}{3\pi(\beta - 4)} = \frac{64}{15\pi}. \tag{3}$$