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Effects of nonlocal elasticity and Knudsen number on fluid–structure interaction in carbon nanotube conveying fluid

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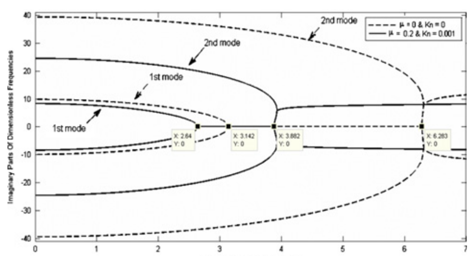
HIGHLIGHT

- Simultaneous small-size effect of both fluid and structure in FSI are considered.
- *Kn* has more remarkable effect than nonlocal parameter on gas nano-flow.
- Nonlocal parameter decreases second critical velocity more than the first one.
- In liquid flow nonlocal parameter causes more reduction in critical velocity than *Kn*.

GRAPHICAL ABSTRACT

Increase in *Kn* and nonlocal parameter, μ, advances flow instabilities in CNTs conveying fluid drastically for liquid nano-flow, as opposed to absence of those effects.



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ABSTRACT

In this paper, we investigate the effect of nano-size of both fluid flow and elastic structure simultaneously on the vibrational behavior of a pinned–pinned and a clamped–clamped nanotube conveying fluid, using both Knudsen number (*Kn*) and nonlocal continuum theory. Euler–Bernoulli plug flow (EBPF) theory is used for modeling fluid–structure interaction (FSI). It is observed that nonlocal parameter has more effect than *Kn* on the reduction of critical velocities of a liquid nano-flow. This effect has considerable impact on the reduction of critical velocities for a clamped–clamped beam in comparison with a pinned–pinned one. We concluded that the dimensionless nonlocal parameter, had more impressive effect on the dimensionless critical flow velocity of the second mode divergence and coupled mode flutter instabilities. However, in a gas nano-flow, the situation is totally different and *Kn* causes more reduction in critical velocities. Furthermore, it is emphasized that ignoring nano-size effects on liquid and gas nano-flow might cause non-conservative design of nano-devices.

1. Introduction

Carbon nanotubes (CNTs) are effectively long and thin cylinders of graphite. Due to perfect hollow cylindrical geometry and superior mechanical strength, CNTs have potential usage as cancer therapy devices or nano-vessels for conveying and storing fluids and drug delivery in bio-nanotechnology [1]. In this regard, a remarkable number of studies have been accomplished to disclose the vibrational behavior of such nano-structures. For instance, Yoon et al. [2] studied the influence of internal flow on free vibration and flow-induced structural instability of CNT. They showed that the internal moving fluid could substantially affect vibrational frequencies especially for suspended, longer and larger-innermost radius CNTs at higher flow velocities. Wang et al. [3] investigated buckling instability of double-walled CNT conveying fluid by using a multi-elastic beam model and showed that the effect of the van der Waals force, slenderness ratio and spring constant of surrounding elastic medium on the critical flow velocity were significant. Zhen et al. [4] showed that the resonant

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frequencies and critical flow velocities were significantly dependent on the properties of the surrounding medium, the boundary conditions and the temperature change. Mahdavi et al. [5] studied nonlinear vibration of an embedded double-walled carbon nanotube (DWCNT) aroused by nonlinear van der Waals (vdWs) interaction forces from both surrounding medium and adjacent tubes. They found that the nonlinear vdW forces from the surrounding medium resulted in non-coaxial vibration of the embedded DWCNT.

In fluid–structure interaction (FSI) problems, specifically in slender structures conveying axial flow, divergence (static buckling) and flutter (dynamic buckling) stabilities establish the core of discussion. For a long time, Flutter, as a post-divergence dynamic phenomenon occurring for conservative systems, i.e., for positively supported 1/D systems such as doubly hinged, doubly clamped, and hinged-clamped boundary conditions, has been a room for debate and ambiguity. In a review article by Wang and Ni [6], in 1977, Done and Simpson [7] opened up a controversial question about the capability of occurrence of post-divergence (flutter) in conservative systems such as beams supported at both end. In the same review [6], in 1978, Holmes [8] answered this question as the title of his paper, "Pipes supported at both ends cannot flutter". His conclusion was based on nonlinear dynamic theory. From these studies, it may be concluded that without conducting a nonlinear analysis for investigating post-divergence (flutter) in FSI problems, it may be not sufficient to draw any conclusion about post-divergence phenomena solely based on a linear analysis. Since this issue is still questionable and under debate; we may disregard such a nonlinear analysis.

In this research, however we are considering small-size effects for both slip boundary conditions on fluid flow and solid structure on the vibrational behavior of CNTs. In the earlier studies, researchers only considered nano-scale effect on either slip boundary condition on fluid flow or structural system; however, in this paper, we investigate both effects simultaneously. In many recent studies, various size-dependent continuum theories have been developed for vibration and instability analysis of CNTs conveying fluid. Ke and Wang [9] investigated vibration and instability of fluid-conveying double-walled carbon nanotubes 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 [10] utilized nonlocal elasticity theory integrated with surface elasticity theory to model the fluid conveying nanotubes with both inner and outer surface layers. He revealed that surface effect was substantial, especially for smaller tube thicknesses or larger aspect ratios. The fundamental frequency predicted by his new model was generally higher than that predicted by the Euler–Bernoulli beam model without surface effects. Wang [11] developed a theoretical analysis of wave propagation of fluid-conveying single-walled carbon nanotubes based on strain gradient elasticity theory. He emphasized that two small-scale parameters related to the inertia and strain gradients significantly affect phase velocity at higher wave numbers. In addition to the above-mentioned theories, most of researchers developed a nonlocal elastic beam model to analyze vibration and instability of CNTs conveying fluid, using theory of nonlocal elasticity. Tounsi et al. [12] made a comment on the work written by Lee and Chang [13] that had been about the vibration analysis of fluid-conveying double-walled carbon nanotubes based on nonlocal elastic theory. Tounsi et al. [12] corrected the equation of motion extracted by Lee and Chang [13] and rederived correct equations. Zhen and Fang [14] investigated thermal and nonlocal effects on the vibration and instability of single-walled CNT conveying fluid and indicated that the natural frequencies and critical flow velocities increased as temperature changes increased, and thermal effect could reduce the influence of nonlocal effect. Rafiei et al. [15] discussed about the effects of taper ratio and small-scale parameter on the vibration of non-uniform carbon nanotubes. They revealed that non-dimensional frequencies obtained from nonlocal theory are less than those obtained from a local theory. In addition, they showed that by increasing the taper ratio, the critical flow velocity decreased. Recently, there have been new trends in formulating nonlocal elasticity theory in engineering communities. Based on [16,17], the earlier trend has been called "partial" nonlocal elasticity, due to ignoring higher-order boundary conditions derived from a variationally consistent formulation, while using nonlocal constitutive law, as a part of equilibrium (static/dynamic), and kinematic (geometric or compatibility) relations. By the same authors, recent trend of nonlocal formulation has been named "exact" nonlocal elasticity, because higher-order terms are derived for both differential equations and boundary conditions of nonlocal boundary-value problem. Wang [18] developed the higher-order governing equation and the boundary conditions based on exact nonlocal stress model to examine the vibration properties and stability of nanotubes conveying fluid. This modified nonlocal beam model for nanotubes conveying fluid readily predicted that the natural frequencies and critical flow velocities are significantly different from those given by the partial nonlocal beam model. Actually, the trends of changes in stiffness, natural frequencies and buckling loads were observed to be completely in opposite for the two theories.

Rashidi et al. [19] presented an innovative model for a single-mode coupled vibrations of nanotubes conveying fluid by considering the small-size effects on the flow field. They formulated the small-size effects on slip boundary conditions of nano-flow through Knudsen number (*Kn*). They reported, for passage of gas through nano-pipe with nonzero *Kn*, the critical flow velocities decreased considerably as opposed to those for zero *Kn* and also nonzero *Kn* has no appreciable effect on the general behavior of CNT conveying liquid. Mirramezani and Mirdamadi [20] revealed that for a clamped-pinned conveying gas fluid, they could see the coupled-mode flutter and mode combination for a *Kn* higher than zero, while they could not observe this phenomenon for a *Kn* equal to zero and other conditions fixed.

A major objective of this study is to propose a model, for the coupled vibrations of carbon nanotubes conveying fluid, taking into account the small-size effects of both flow field and solid structure in CNTs using Knudsen number and nonlocal continuum theory. We have studied the influences of both small-size effects on the critical velocities, velocities at which divergence and flutter instabilities may occur. It could be seen that these effects had significant influences on the dimensionless critical flow velocities for both pinned-pinned and clamped–clamped boundary conditions especially when the fluid flow is a gas. For numerical solution, we have discretized pined-pined and clamped–clamped beam by choosing two generalized coordinates in order to show flutter instability in addition to divergence instability in the first and second modes of nano-beam vibrations.

The remainder of this study is organized as follows: In Section 2, we re-formulate the fluid–structure interaction (FSI) governing equations by considering small-size effects of both flow field and elastic structure. In Section 3, we implement the Galerkin weighted-residual solution technique and solve the partial differential equations of nanotube vibrations. In Section 4, we discuss about stability analysis and present the results. Finally, in Section 5, we express our conclusions.

2. Nonlocal and Kn-dependent fluid–structure interaction (FSI) equation

In this section, we devise a nonlocal FSI formulation depending on *Kn*. The dependency is applied by the definition of a *Kn*-dependent flow velocity. The conventional governing equation