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On nonlinear stability of fluid-conveying imperfect micropipes

Amir Mehdi Dehrouyeh-Semnani*, Mansour Nikkhah-Bahrami, Mohammad Reza Hairi Yazdi

School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

Micropipe conveying fluid as a core element can be found in many microfluidic devices. In such scale, size effect phenomenon in micropipe may play a significant role in the mechanical behavior of system. In addition, due to the improper production process, the micropipe may be fabricated with a geometric imperfection. Hence, this study objects to investigation of the size-dependent and -independent stability behavior of geometrically perfect and imperfect extensible micropipe conveying fluid under different boundary conditions. In the framework of modified couple stress theory, the nonlinear equations of system are established based on Euler-Bernoulli beam theory. Statics-based analytical solutions are developed to study the nonlinear stability characteristics of system. The statics-based results are verified by aid of a dynamics-based numerical solution. It is indicated that for a perfect case the system becomes unstable at a critical velocity via a pitchfork bifurcation. But, for an imperfect case the system may lose its stability at a primary critical velocity by a perturbed pitchfork bifurcation also it becomes unstable at a secondary critical velocity by a transcritical bifurcation. It is found that the primary and secondary critical velocities of the imperfect case are, respectively, smaller and greater than the critical velocity of the perfect case. A parametric study is conducted to highlight the influence of different dimensionless parameter as well as boundary conditions on the nonlinear stability behavior of system. Finally, it should be pointed out that the analytical solution and the presented results not only for the size-dependent pipe conveying fluid in micro scale but also for the size-independent pipe conveying fluid from macro to micro scale can be utilized.

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1. Introduction

The experimental tests (Lam, Yang, Chong, Wang, & Tong, 2003; Lei, He, Guo, Li, & Liu, 2016) revealed that the classical continuum theory is incapable of predicting the mechanical behavior of microstructures when the size effect phenomenon occurs. To overcome this deficiency, various high-order continuum theories have been developed. Yang, Chong, Lam and Tong (2002) proposed a modified couple stress theory which is capable of describing the size effect phenomenon by only one material length scale parameter in addition to Lame's parameters. The newly developed theory obtained by introducing an additional equilibrium relation to govern the behavior of the couples. The relation restricts the deviatoric part of couple stress tensor to be symmetric and also the strain and symmetric curvature tensors are the deformation measures conjugate to the symmetric stress and the deviatoric couple stress tensors, respectively. Many researchers have implemented this higher-order continuum theory to develop the size-dependent mathematical model of micro/nano-structures as well as to

* Corresponding author.
E-mail addresses: a.m.dehrouye@ut.ac.ir, a.m.dehrouye@gmail.com (A.M. Dehrouyeh-Semnani).

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investigate the role of size-dependency in the mechanical characteristics of them (Attia & Mohamed, 2017; Bakhshi Khaniki & Hosseini-Hashemi, 2017; Fakhrabadi, 2017; Fakhrabadi, Rastgoo, Ahmadian, & Mashhadi, 2014; Farokhi & Ghayesh, 2015; Farokhi, Païdoussis, & Misra, 2016; Ghayesh & Farokhi, 2017b; Ghayesh, Farokhi, Gholipour, & Tavallaeinejad, 2017; Krysko, Awrejcewicz, Pavlov, Zhigalov, & Krysko, 2017; Li & Pan, 2015; Mojahedi, 2017; Mustapha & Hawwa, 2016; Saadatnia, Askari, & Esmailzadeh, 2017; Shojaeian & Zeighampour, 2016; Togun & Bağdatli, 2016; Yang & Chen, 2015; Zeighampour & Shojaeian, 2017).

Owing to the rapid developments in micro-electro-mechanical systems (MEMS), the microstructures containing fluid flow are now present in many microfluidic devices. They have many potential applications as sensors, actuators, resonators, drug delivery devices and fluid filtration devices (Bhardwaj, Bagdi, & Sen, 2011; Haneveld et al., 2010; Huber, 2016; Monge et al., 2017; Sajeesh & Sen, 2014; Sparks et al., 2009). Recently, (Rinaldi, Prabhakar, Vengallatore, & Païdoussis, 2010) reported that the inside diameter of circular fluid-conveying micropipes are considered ranged from 1 to 100 μm. Hence, size-dependent stability and dynamics of microstructures conveying fluid based on modified couple stress theory have been investigated by some researchers. (Wang, 2010) studied linear stability and free vibration of fluid-conveying micropipe based on Euler Bernoulli beam theory. (Wang, Liu, Ni, & Wu, 2013) examined in- and out-of-plane free vibration of clamped-clamped micropipe conveying fluid incorporating the influence of fluid flow regime. (Yang, Ji, Yang, & Fang, 2014) studied nonlinear free vibration and post-buckling of pinned-pinned microtubes via use of a semi-analytical method. (Tang, Ni, Wang, Luo, & Wang, 2014) proposed a nonlinear model for three-dimensional analysis of curved micropipes conveying fluid. (Zeighampour & Tadi Beni, 2014) investigated linear free vibrations and instability of fluid-conveying DWCNT under visco-Pasternak foundation based on Donnell's shell model. (Ansari, Gholami, Norouzzadeh, & Sahmani, 2015) analyzed linear free vibration and stability of functionally graded fluid-conveying microshell with pinned-pinned boundary conditions via the first-order shear deformation shell theory. (Kural & Özkaya, 2015) investigated nonlinear free vibration of a doubly-clamped micropipe conveying fluid resting on elastic foundation. (Mashrouteh, Sadri, Younesian, & Esmailzadeh, 2016) examined nonlinear free vibration of viscoelastic microtubes conveying fluid with pinned-pinned boundary conditions by means of variational iteration method. (Dehrouyeh-Semnani, Zafari-Koloukhi, Dehdashti, & Nikkhah-Bahrami, 2016b) performed a comprehensive study on nonlinear flow-induced dynamics of cantilevered micropipe conveying fluid in post-flutter domain. (Hu, Wang, Dai, Wang, & Qian, 2016) analyzed nonlinear and chaotic dynamics of cantilevered micropipes conveying fluid. (Dehrouyeh-Semnani, Nikkhah-Bahrami, & Hairi Yazdi, 2017b) examined nonlinear resonant dynamics of a simply supported micropipe conveying fluid in subcritical domain via analyzing frequency-response and force-response curves. (Mohammadimehr & Mehrabi, 2017) investigated stability and free vibration characteristics of double-bonded micro composite sandwich cylindrical shell conveying fluid flow using Reddy shell theory. (Hosseini, Maryam, & Bahaadini, 2017) performed a numerical analysis on forced vibrations of double piezoelectric fluid-conveying FG micropipes carrying a moving load based on the flexoelectricity theory. (Deng, Liu, & Liu, 2017) analyzed free vibration and stability of multi-span FGM micropipes conveying fluid by combining reverberation-ray matrix method and wave propagation method.

In micro scale, it is very likely to produce microstructures with geometric imperfection because of the improper fabrication process. The mechanical behavior of geometrically imperfect microstructures may be totally different from the perfect ones (Dehrouyeh-Semnani, Mostafaei, & Nikkhah-Bahrami, 2016a; Dehrouyeh-Semnani, Mostafaei, Dehrouyeh, & Nikkhah-Bahrami, 2017a; Farokhi & Ghayesh, 2015; Farokhi & Ghayesh, 2016; Farokhi, Ghayesh, & Amabili, 2013; Farokhi, Ghayesh, Kosasih, & Akaber, 2016; Farokhi, Misra, & Païdoussis, 2017; Ghayesh & Amabili, 2014; Ghayesh & Farokhi, 2015a, b, 2017a; Ghayesh, Farokhi, & Gholipour, 2017; Ghayesh, Farokhi, Gholipour, Hussain, & Arjomandi, 2017; Shojaeian, Yaghoub Tadi, & Hossein, 2016). Based on the best knowledge of authors, there is no single study related to the size-dependent mechanical behavior of geometrically imperfect micropipe conveying fluid based on modified couple stress theory. Therefore, this study aims to explore analytically the nonlinear size-dependent stability characteristic of geometrically imperfect extensible micropipe conveying fluid under different boundary conditions. The outline of the paper is as follows: In Section 2, the size-dependent nonlinear governing equations and boundary conditions of a geometrically imperfect Euler-Bernoulli extensible micropipe conveying fluid are proposed in the framework of modified couple stress theory. In Section 3, a statics-based analytical solution is developed to evaluate the equilibrium paths of system with and without geometric imperfection for different boundary conditions. In Section 4, the integro-partial differential equation of motion is discretized into a set of ordinary differential equations via aid of Galerkin procedure. Subsequently, the resulting equations are numerically solved by use of an embedded Runge–Kutta method. In Section 5, the stability response of system is analytically investigated by incorporating the influences of different parameters. In addition, the statics-based analytical results are verified with the dynamics-based numerical results. Finally, some size-independent numerical results of a pinned-pinned system available in the literature are compared with the analytical and numerical results of present work. The paper concludes with Section 6, where the work is summarized and the final remarks are provided.

2. Mathematical formulation

As shown in Fig. 1, the system under consideration consists of a horizontal micropipe of length L, cross-sectional area A, second moment of cross-sectional area about the y-axis I, Young's modulus E, shear modulus G, material length scale parameter ℓ, density ρ_p, and mass per unit length m conveying fluid of density ρ_f, and mass per unit M with flow velocity U. In addition, the micropipe is longitudinally constrained at both ends.

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