International Journal of Engineering Science 101 (2016) 1–13

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

Size dependent stability analysis of cantilever micro-pipes conveying fluid based on modified strain gradient theory

Mohammad Hosseini*, Reza Bahaadini

Department of Mechanical Engineering, Sirjan University of Technology, 78137-33385 Sirjan, Iran

ARTICLE INFO

Article history:
Received 13 December 2015
Accepted 30 December 2015
Available online 23 January 2016

Keywords:
Micro-pipes
Modified strain gradient theory
Cantilever
Flutter instability

ABSTRACT

In this paper, size dependent stability analysis of cantilever micro-pipes conveying fluid is investigated. The mathematical derivations are expanded in terms of three length scale parameters using the modified strain gradient theory (MSGT) in conjunction with the Euler–Bernoulli beam model. The MSGT encompasses modified couple stress theory (MCST) and classical theory (CT) when two of three length scale parameters or all of them are taken to be zero, respectively. The size dependent governing equation and associated boundary conditions are derived by applying extended Hamilton's principle and are discretized through the extended Galerkin method. An eigen analysis is performed and a parametric study is then carried out to examine the effect of length scale parameter, outside diameter and aspect ratio on the natural frequencies and the flutter critical speeds. Results affirm that MSGT predicts greater natural frequencies and more flutter critical speeds than that predicted by MCST and CT.

1. Introduction

Numerous investigations in the field of fluid structure interaction (FSI) have been performed to vibration and stability studies of macro-pipe conveying fluid. The dynamic behavior of articulated pipe conveying fluid was reported by Benjamin (1961a, 1961b). Gregory and Paidoussis (1966a, 1966b) showed that cantilevered pipes conveying fluid can lose their stability by flutter at sufficiently high flow velocities. Guo, Zhang, and Païdoussis (2010) studied the effects of laminar and turbulent flow profiles on the flutter instability of pipe conveying fluid. Hosseini and Fazelzadeh (2011) carried out an investigation on the stability of a functionally graded cantilevered pipe conveying fluid with considering axial end force and thermal field. Wang and Dai (2012) investigated the effects of two symmetric elbows fitted at downstream end on the stability of simply supported and cantilevered pipes conveying fluid. Firouz-Abadi, Askarian, and Kheiri (2013) studied the bending-torsional stability of a cantilevered pipe conveying fluid subjected to an inclined terminal nozzle at its end section. Yu, Païdoussis, Shen, and Wang (2013) employed a novel transfer matrix method to study flutter instability behavior of a periodic pipe carrying fluid for clamped-free boundary condition. Kheiri, Païdoussis, Del Pozo, and Amabili (2014) investigated the dynamics of a conveying-fluid pipe with flexible supported at the ends.

Due to the recent technological development in science and engineering, micro- and nano-pipes conveying fluid are key components of many structures and commonly seen in numerous engineering applications such as fluid storage, drug delivery and micro-and nano-fluidic devices (Foldvari & Bagonluri, 2008; Gao & Bando, 2002; Hummer, Rasaiah, & Noworyta, 2001).

* Corresponding author. Tel.: +98 34 42 33 69 01; fax: +98 34 42 33 69 00.
E-mail address: hosseini@sirjantech.ac.ir, moh_hosseini@yahoo.com (M. Hosseini).

http://dx.doi.org/10.1016/j.ijengsci.2015.12.012

In the last two decades, experimental studies in the size-dependent deformation behavior of micro-structures can be pursued in the work of Lam and Chong (1999), Ma and Clarke (1995) and McFarland and Colton (2005). They showed that the sized-effect plays the key role in micro-structures and indicated that classical continuum mechanics is not capable of predicting sized-effect on the mechanical behaviors. So far, some size-dependent continuum theories including Eringen's nonlocal, modified couple stress and strain gradient theories have been discussed.

The classical couple stress theory is one of the higher-order continuum theories which considers the rotational gradients. It comprises two additional non-classical length scale parameters in addition to the two classical Lame parameters for isotropic elastic materials (Koiter, 1964; Mindlin & Tiersten, 1962). Yang, Chong, Lam, and Tong (2002) developed modified couple stress theory by introducing only one material length scale parameter which demonstrates the effect of micro-size. Mohammad-Abadi and Daneshmehr (2014, 2015) studied the dynamic and buckling analysis of micro composite laminated beams based on modified couple stress theory. Wang and Liew (2007) investigated the effect of small length scale on the vibration and instability of tubular micro- and nano-beams containing internal fluid flow. Tang, Ni, Wang, Luo, and Wang (2014b) developed a theoretical model for three-dimensional vibration of a clamped-clamped curved pipe conveying fluid and investigated the effects of open angle, small length scale and speed of fluid on the vibrational characteristics. Dai, Wang, and Ni (2015) studied the dynamics and pull-in instability of micro-beams conveying fluid. They discussed about the effect of material length scale, non-uniform profile of the flow velocities and nonlinear electro-statical force on the natural frequency and instability of the micro-beam. Wang, Liu, Ni, and Wu (2013) studied the dynamics of micro-pipes conveying fluid using the size effects of micro-beam and micro-flow. They considered clamped-clamped straight and curved pipes and investigated the effect of material length scale parameter and size effect of micro-flow on the natural frequency and fluid velocity. Xia and Wang (2010) further developed a conveying-fluid micro-pipe using Timoshenko beam model in conjunction with modified couple stress theory. They discussed the effect of material length scale parameter and Poisson ratio on the natural frequency and divergence critical speed of a micro-pipe with supported ends. Ahangar, Rezazadeh, Shabani, Ahmadi, and Toloei (2011) presented a modified couple stress theory for vibration analysis of micro-pipes conveying fluid and considered the effects of material length scale parameter on the eigen-frequencies and divergence critical fluid speed. Kural and Özkaya (2015) analyzed clamped-clamped micro-pipe conveying fluid using modified couple stress model and investigated the effects of micro-structure, elastic foundation and the occupancy rate of micro-beam on vibrations.

In order to consider the micro size effect, the strain gradient theory utilizes two classical Lame constants and five additional length scale parameters (Mindlin & Eshel, 1968) and contains both of anti-symmetric and symmetric parts of the higher order deformation gradients. Lam, Yang, Chong, Wang, and Tong (2003) developed modified strain gradient theory in which three length scale parameters appear in the constitutive equation. Akgöz and Civalek (2012) studied the influence of length scale parameters on the static response of micro-beams using modified strain gradient theory. They used analytical solutions for deflection and rotation of micro-beams for various boundary conditions. In another works, Akgöz and Civalek (2011, 2013) investigated the static bending, buckling and vibration behavior of micro-beams based on modified strain gradient elasticity theory. Yin, Qian, and Wang (2011) studied vibration and stability of simply supported micro-pipe conveying fluid by considering modified strain gradient theory and investigated the effect of length scale parameters and outside diameter on the natural frequency and the fluid velocity. In addition to the linear analysis, some works were devoted for nonlinear vibrations analysis of micro-structures by using the modified couple stress theory and the modified strain gradient theory (Asghari, Kahrobaiyan, & Ahmadian, 2010; Karparvarfard, Asghari, & Vatankhah, 2015; Li & Hu, 2015; Rahaeifard, Kahrobaiyan, Ahmadian, & Firoozbakhsh, 2013; Setoodeh & Afrahim, 2014; Tang, Ni, Wang, Luo, & Wang, 2014a; Yang, Ji, Yang, & Fang, 2014).

Up to now, many studies have been carried out to investigate the effect of length scale and other physically parameters on natural frequencies and critical divergence speeds of micro-pipes conveying fluid supported at two end. The present work attempts to illuminate effects of size dependent on critical flutter and bifurcation speeds of cantilever micro-pipes containing fluid flow. Based on the modified strain gradient theory, the governing equation of motion and related boundary conditions are obtained via variational Hamilton's principle. By using an extended Galerkin's approximate method, partial differential equations are converted to ordinary differential equations. The effects of material length scale parameter, outside diameter and aspect ratio on the natural frequencies and critical flutter speeds of cantilevered micro-pipes conveying fluid are studied in detail.

2. Theoretical formulation

Consider a cantilevered micro-pipe of length L, mass per unit length m_p, cross-sectional area A and effective flexural rigidity EI, as shown in Fig. 1. Suppose that incompressible fluid with mass per unit length m_f and axial flow velocity U flows through the nanotube.

According to the modified strain gradient theory, the strain energy density is a function of the symmetric strain tensor, the dilatation gradient vector, the deviatoric stretch gradient tensor and the symmetric rotation gradient tensor (Kong, Zhou, Nie, & Wang, 2009; Lam et al., 2003). Consequently, the stored strain energy E_e in a continuum made of an isotropic linear elastic material occupying region V with infinitesimal deformations can be obtained as follows:

$$E_e = \frac{1}{2}\int_V \left(\sigma_{ij}\varepsilon_{ij} + p_i\gamma_i + \tau^{(1)}_{ijk}\eta^{(1)}_{ijk} + m_{ij}\chi_{ij}\right)dV \quad (1)$$