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Size-dependent frequency and stability characteristics of axially moving microbeams based on modified couple stress theory

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ABSTRACT

This investigation aims to explore dynamic characteristics of axially moving Timoshenko microbeams by taking into account size-dependency based on a modified couple stress theory. Size-dependent motion equations and associated boundary conditions are established via Hamilton's principle. In addition, size-dependent axially moving Euler–Bernoulli beam model can be recovered from the present Timoshenko beam model by reinstating the normality assumption. Galerkin method is applied to discretize the partial differential equations into a set of ordinary differential equations, and then the size-dependent dynamic characteristics of axially moving microbeams with simply supported and doubly clamped boundary conditions are numerically determined. It is observed that the microbeams lose stability via a divergence bifurcation in the first mode. The results illustrate that the critical velocity in which the instability occurs and also the natural frequencies significantly increase when the role of size-dependency is of great importance. Finally, the sensitivity of frequencies to velocity and also the influence of size-dependent shear deformation on frequencies and critical velocities are examined.

1. Introduction

Nowadays, microbeam as a continuous element has been widely used in micro electro mechanical systems (MEMS), such as the V-beam structure as a mechanical amplification in the Fabry–Pérot optical accelerometer (Davies, George, Gower, & Holmes, 2014), micro-beam sensor for decteion of thermal conductivity (Takamatsu, Fukunaga, Tanaka, Kurata, & Takahashi, 2014), electrostatically actuated initially curved microbeams (Medina, Gilat, Ilic, & Krylov, 2014), multi-beam microaccelerometer for vibration monitoring in intelligent manufacturing equipment (Liu, Zhao, Wang, Sun, & Jiang, 2013b), electro-thermal micro-actuator for application to dual-stage positioning systems of hard disk drives (Yang, Lau, Tan, Chong, Thubthimthong, & He, 2012), electrostatic microgripper system for microassembly applications (Hamedi, Salimi, & Vismeh, 2012) and dual-axis micro-mechanical probe (Amakawa, Fukuzawa, Shikida, Tsuji, Zhang, & Itoh, 2012). On the other hand, the experimental tests have been proven that the classical continuum theories are incapable of predicting mechanical behavior of microstructures when the size of microstructures reduces (Fleck, Muller, Ashby, & Hutchinson, 1994; Lam, Yang, Chong, Wang, & Tong, 2003; Motz, Schöberl & Pippan, 2005; Liu, He, Dunstan, Zhang, Gan, Hu, & Ding, 2013a). Recently, a higher-order elasticity theory was developed by

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Yang, Chong, Lam and Tong (2002) which is capable of explaining the size-dependency in microstructures by employing one material length scale parameter in addition to Lamé parameters.

Concerning taking into account the size-dependency for structures in small-scale based on modified couple stress theory developed by Yang et al. (2002), there exists a large body of investigations in the literature. Some of these investigations can be outlined as: an Euler–Bernoulli beam model for static bending analysis and comparison with experimental results by Park and Gao (2006), an Euler–Bernoulli beam model for dynamic analysis of microbeams by Kong, Zhou, Nie and Wang (2008), a Timoshenko beam model for static and dynamic analyses by Ma, Gao and Reddy (2008), a nonlinear Euler–Bernoulli beam model for static bending, free vibration and post buckling analyses by Xia, Wang and Yin (2010), a nonlinear Timoshenko beam formulation for static and vibration analyses by Asghari, Kahrobaiyan and Ahmadian (2010), buckling analysis of axially loaded micro-scaled beams based on Euler-Bernoulli beam theory by Akgöz and Civalek (2011), wave propagation characteristics of a twisted micro-scale beam by Mustapha and Zhong (2012), composite laminated Kirchhoff, Mindlin and Reddy plate models by Chen, Xu and Li (2012), nonlinear free vibration of functionally graded microbeams by Ke, Wang, Yang and Kitipornchai (2012), free vibration analysis of axially functionally graded tapered Bernoulli–Euler microbeams by Akgöz and Civalek (2013), functionally graded Kirchhoff and Mindlin plate models by Thai and Choi (2013), a Mindlin plate finite element for static bending, buckling and dynamic analysis by Zhang, He, Liu, Gan and Shen (2013), dynamic stability analysis of functionally graded higher-order shear deformable microshells by Sahmani, Ansari, Gholami and Darvizeh (2013), static and dynamic analyses of third-order shear deformation functionally graded micro-beams by Nateghi and Salamat-Talab (2013), a comparison investigation between constitutive and Euler–Bernoulli beam models by Dehrouyeh-Semnani (2014), thermo-mechanical buckling behavior of functionally graded microbeams embedded in elastic medium by Akgöz and Civalek (2014), axisymmetric postbuckling analysis of size-dependent functionally graded annular microplates using the physical neutral plane by Ke, Yang, Kitipornchai and Wang (2014), three-dimensional vibration analysis of curved microbeams under fluid force induced by external flow by Tang, Ni, Wang, Luo and Wang (2014), development of a thin conical shell model and free vibration analysis by Zeighampour and Tadi Beni (2014), simulation of fluid–solid interaction in a microchannel using a combination of Lattice–Boltzmann method and finite element method by Esfahanian, Dehdashti and Dehrouyeh-Semnani (2014a, 2014b), nonlinear-electrostatic analysis of micro-actuated beams incorporating surface elasticity effect by Shaat and Mohamed (2014), buckling analysis of Euler–Bernoulli and Timoshenko laminated microcomposite using generalized differential quadrature method by Mohammad Abadi and Daneshmehr (2014), discussion on evaluation of material length scale parameter based on micro-cantilever test by Dehrouyeh-Semnani and Nikkhah-Bahrami (2015a), forced vibration analysis of a microplate subjected to a moving load based on Kirchhoff–Love plate theory by Şimşek, Aydın, Yurtcu and Reddy (2015), stability analysis of a fluid-conveying micro-pipe axially loaded with a pair of piezoelectric layers located at its top and bottom surfaces based on Euler–Bernoulli beam theory by Abbasnejad, Shabani and Rezazadeh (2015), nonlinear bending and postbuckling of functionally graded Mindlin rectangular microplates considering the physical neutral plane position by Ansari, Gholami, Faghih Shojaei, Mohammadi and Darabi (2015), mechanical behavior of functionally graded sandwich microbeams by Thai, Vo, Nguyen and Lee (2015), thermo-mechanical dynamics of perfect and imperfect Timoshenko microbeams by Farokhi and Ghayesh (2015), thermal buckling analysis of microcomposite laminated based on Euler–Bernoulli, Timoshenko and Reddy beam theories by Mohammadabadi, Daneshmehr and Homayounfard (2015), dependency of material length scale parameter on higher-order elasticity theory unlike Lame's constants by Dehrouyeh-Semnani (2015a), static, dynamic and buckling analyses of orthotropic Kirchhoff-type skew micro-plates and comparison with nonlocal elasticity theory by Tsiatas and Yiotis (2015), static and dynamic analyses of functionally graded annular and circular microplates by consideration of spatial variation of the length scale parameter by Eshraghi, Dag and Soltani (2015), nonlinear bending and free vibration responses of a simply supported functionally graded microplate lying on an elastic foundation based on Kirchhoff/Mindlin plate theory together with the von Karman's geometric nonlinearity by Lou and He (2015), eigenanalyses of functionally graded microbeams entrapped in an axially-directed magnetic field with elastic restraints by Mustapha and Hawwa (2015), static bending and free vibration analyses of a functionally graded piezoelectric microplate based on sinusoidal plate theory by Li and Pan (2015), investigation of flapwise vibration behavior of a rotating Euler–Bernoulli and Timoshenko microbeams at a constant angular speed using finite element method by Dehrouyeh-Semnani (2015b), nonlinear free vibration analysis of axially functionally graded Euler–Bernoulli microbeams with immovable ends by using von-Kármán's nonlinear strain–displacement relationships and He's variational method by Şimşek (2015), investigation of small-scale effects on the three-dimensional flexural vibration characteristics of a micro-rotating shaft–disk system as a basic model for micro-engines by Hashemi and Asghari (2015), development of a nonlinear model for cantilevered microbeams and exploring the nonlinear dynamics i.e., frequency–response curves, phase portraits and time histories by Dai, Wang and Wang (2015), free vibration analysis of sigmoid functionally graded beams in small-scale based on general shear deformation theory by Akbarzadeh Khorshidi and Shariati (2015), exact closed-form free vibration analysis for functionally graded microplates based on three-dimensional elasticity theory by Salehipour, Nahvi and Shahidi (2015), a new model for functionally graded microplates by using a four variable refined plate theory and also a closed-form solution for bending, buckling and free vibration analyses of simply supported rectangular microplates by He et al. (2015), viscoelastically damped sandwich microbeams with homogenous and functionally graded face layers for vibration damping by Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari and Nikkhah-Bahrami (2015a, 2015b) and nonlinear parametric vibration and stability of microbeams due to time-dependent longitudinal excitation load by Ghayesh, Farokhi and Alici (2015).

Dynamic characteristics of axially moving beams in macro/micro-scales based on the classical theories have been widely investigated (Pellicano & Vestroni, 2002; Ghayesh & Balar, 2008; Tang, Chen, & Yang, 2008; Ghayesh, 2011; Marynowski, 2012; Ghayesh & Amabili, 2013; Tang, Chen, Zhang, & Yang, 2013; Marynowski & Kapitaniak, 2014; Yan, Ding, & Chen, 2014; Lv, Li, Li, & Liu, 2014; Ni et al., 2014; Zenkour, Abouelregal, & Abbas, 2014; Ghayesh & Farokhi, 2015; Li, Ni and Wang, 2015;