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Viscoelastically coupled size-dependent dynamics of microbeams

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ABSTRACT

This paper investigates the viscoelastically coupled size-dependent dynamics of a microbeam in the framework of the modified couple stress theory. The elastic and viscous components of the stress and deviatoric part of the symmetric couple stress tensors are obtained employing the Kelvin–Voigt viscoelastic model. The size-dependent elastic potential energy is developed based on the modified couple stress theory. The work of the viscous components of the stress and deviatoric part of the symmetric couple stress tensors are formulated in terms of the system parameters. The work of an external excitation force as well as the kinetic energy of the system is obtained as functions of the displacement field. Hamilton's principle is employed, yielding the nonlinear equations for the longitudinal and transverse motions of the viscoelastic microbeam. A weighted-residual method is then applied to the nonlinear equations of motion resulting in a high-dimensional reduced-order system with finite degrees of freedom. This high-dimensional model is solved via use of a continuation method as well as a direct time-integration technique. The viscoelastically size-dependent nonlinear frequency- and force-responses are constructed and the effects of the simultaneous presence of viscoelastic energy dissipation mechanism and the length-scale parameter are examined.

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1. Introduction

The dynamical behaviour of microscale elements such as microplates and microbeams has been the subject of many investigations in recent years, mainly due to their extensive applications as core elements in many micromachines and microdevices (such as microactuators, vibration sensors, biosensors, micro energy harvesters, and airbag accelerometers) (Asghari, Kahrobaiyan, & Ahmadian, 2010, Baghani, 2012, Ghayesh, Farokhi, & Alici, 2016, Mojahedi & Rahaeifard, 2016). These microelements are usually subject to dynamic/static loadings, causing them to either oscillate or deform; this necessitates the analysis of their motion for better performance purposes.

One important issue in the theoretical motion analysis of microbeams is to take into account internal energy dissipation (while the system is oscillating) – i.e. a *viscoelastic* model, rather than an *elastic* model, should be considered. On the other hand, it has been proven that the deformation/oscillation of microbeams is highly size-dependent (Akgöz & Civalek, 2013, Akgöz & Civalek, 2011, Dehrouyeh-Semnani, 2014, Ghayesh, Amabili, & Farokhi, 2013a, Hosseini & Bahaadini, 2016, Kahrobaiyan, Rahaeifard, Tajalli, & Ahmadian, 2012, Karparvarfard, Asghari, & Vatankhah, 2015, Kong, Zhou, Nie, & Wang, 2008, Mojahedi & Rahaeifard, 2016, Taati, 2016). The modified couple stress theory

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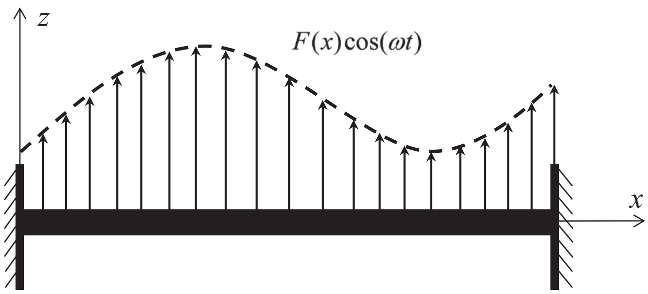

Fig. 1. Schematic representation of a clamped-clamped viscoelastic microbeam subject to a transverse distributed excitation load.

(Dai, Wang, & Wang, 2015, Dehrouyeh-Semnani, BehboodiJouybari, & Dehrouyeh, 2016, Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015, Farokhi & Ghayesh, 2016, H. Farokhi & Ghayesh, 2015a, H. Farokhi, Ghayesh, & Amabili, 2013a, Ghayesh & Farokhi, 2015, Ghayesh, Farokhi, & Amabili, 2013b, Li & Pan, 2015, Şimşek, 2010, Şimşek & Reddy, 2013, Tang, Ni, Wang, Luo, & Wang, 2014) along with the Kelvin-Voigt energy dissipation mechanism is employed in this paper in order to model the simultaneous effects of the length-scale parameter and the internal energy dissipation.

The literature on the size-dependent statics/dynamics of microbeams employing *elastic* models is quite large (H. Farokhi & Ghayesh, 2015b, Ghayesh et al., 2015). Starting with linear models, for instance, Kong et al. (2008) obtained the size-dependent natural frequencies of an Euler-Bernoulli microbeam type. Asghari et al. (2011), by means of the modified couple stress theory, formulated the size-dependent behaviour of a Timoshenko microbeam. Farokhi et al. (2013b) analysed the nonlinear dynamical behaviour of microbeams in postbuckling regime based on the modified couple stress theory. Akgöz & Civalek (2012) employed both the modified and classical couple stress theories in order to analyse the size-dependent buckling response of a longitudinally forced microbeam. Nateghi et al. (2012) examined the size-dependent buckling behaviour of a functionally graded microbeam in the framework of the modified couple stress theory. Zhang et al. (2014) developed a model of a functionally graded third-order shear deformable microbeam via use of a strain gradient elasticity. Salamat-talab, Nateghi, and Torabi (2012) analysed the static and dynamic behaviours of a functionally graded third-order shear deformable microbeam on the basis of the modified couple stress theory.

The studies on the static/dynamics of microbeams were extended in Zhang and Fu (2012) to include viscosity; this study analysed the *static* pull-in instability based on a *single mode* truncation and taking into account *only the transverse motion*.

This paper, for the first time, analyses the size-dependent nonlinear forced dynamics of a microbeam taking into account internal energy dissipation employing a high-dimensional reduced order model as well as conducting stability analysis. Moreover, for the first time, both the longitudinal and transverse displacements and inertia are considered for the dynamic analysis of a viscoelastic microbeam. More specifically, the viscous components of the deviatoric part of the symmetric couple stress tensor as well as those of the stress tensor are formulated and the corresponding work and elastic energy are obtained as functions of the displacement field via use of the constitutive relations and the modified couple stress theory. The viscous work and size-dependent elastic energy are dynamically balanced with the work of the external transverse forcing together with the kinetic energy of the microbeam. A high-dimensional reduced-order model is obtained by means of a weighted-residual method. The frequency and force-responses are constructed by means of a continuation technique along with a direct time-integration method. The effect of the simultaneous presence of viscosity and the length-scale parameter on the resonant response of the system is investigated.

2. Equation of longitudinal and transverse motions

Shown in Fig. 1 is a viscoelastic microbeam of length L, mass density ρ, Young's modulus E, cross-sectional area A, second moment of area I, thickness h, and the length-scale parameter l. The axial and transverse displacements are denoted by $u=u(x,t)$ and $w=w(x,t)$, respectively, with x and t being the axial coordinate and time, respectively. The viscoelastic microbeam is excited by a harmonic excitation force per unit length of $F(x)\cos(\omega t)$ in the transverse direction.

The following assumptions have been made in the system modelling: (*i*) the Euler-Bernoulli beam theory (stating that the cross-sections remain perpendicular to the centreline of the microbeam) is employed; (*ii*) the planar motion (including both the transverse and longitudinal) is considered (*i.e.*, the out-of-plane motion is neglected); (*iii*) the cross-section of the viscoelastic microbeam is assumed to be constant over the entire length; (*iv*) an internal energy dissipation mechanism is considered based on the Kelvin-Voigt scheme; (*v*) the type of nonlinearity is geometric due to stretching; (*vi*) the size effect is modelled through using the modified couple stress theory.

The components of the displacement field of the microbeam can be written as

$$u_x = u(x,t) - z\frac{\partial w(x,t)}{\partial x}, \qquad u_y = 0, \qquad u_z = w(x,t). \tag{1}$$

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