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On size-dependent vibration of rotary axially functionally graded microbeam

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ABSTRACT

Study of the mechanical properties of axially functionally graded (AFG) microbeams is a challenging work due to the varying mechanical properties of these microbeams along the axis. In the present study, the transverse vibration of a rotary tapered AFG Euler–Bernoulli microbeam is studied based on the modified couple stress theory by considering the axial forces which are due to the rotation, in the form of true spatial variation. The governing equations and boundary conditions are derived according to the Hamilton's principle and the governing equations are solved with the aid of the generalized differential quadrature element method (GDQEM). The effects of the small-scale parameter, length and width of the beam, rate of cross-section change and nondimensional angular velocity on the vibration behavior of the non-uniform microbeam are studied for cantilever and propped cantilever boundary conditions. The vibrational behavior of AFG microbeam is also compared with pure metal and pure ceramic. The results are useful in designation of micromachines such as micromotors and micro-rotors.

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1. Introduction

Many micro- and nano-systems cannot be analyzed properly without analysis of their structural elements such as beams. In addition to researches which study the designation of the nanosystems (Li et al., 2014), there have been a wide range of studies to analyze the vibration behavior of micro- and nano-systems.

Due to the widespread applications of beams in micro- and nano-systems, a lot of researchers have tried to find new theories that consider the material size effect and have a material length scale parameter. Many experimental tests have been done to find the most compatible theory and proved that the classical continuum-based theories cannot be applied to micro-structures due to their size effect (Koiter, 1964, Mindlin & Tiersten, 1962, Toupin, 1962). In order to define micro-materials behavior higher order continuum theories are required. Couple stress theory is one of the higher order elasticity theories which was first proposed and amended by Mindlin and Tiersten (1962), Toupin (1962) and Koiter (1964). It consists of two non-classical length scale parameters in addition to Lame's moduli. Yang, Chong, Lam, and Tong (2002) proposed a modified couple stress theory, which contained only one length scale constant. The modified couple stress theory is one of the strongest theories which helps researchers to study the behavior of materials at micro scales. Park and Gao studied the transverse vibration of a Bernoulli–Euler beam model to predict the size effect at micro scales utilizing this theory (Park & Gao, 2006). In other studies, vibration and dynamic analysis of microbeams are done by Kong, Zhou, Nie, and Wang (2008) and Şimşek (2010) on the basis of the modified couple stress theory. A strain gradient theory of rate independent

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plasticity was presented by Fleck, Muller, Ashby, and Hutchinson (1994), using the dislocation theory. Mindlin and Eshel (1968) introduced a strain gradient theory which is one of the first higher order continuum models which deals with five micro-scaled size dependent constants. Moreover Lam, Yang, Chong, Wang, and Tong (2003) developed a strain gradient elastic bending theory for plane-strain beams. They also represented a new set of higher-order metrics to characterize strain gradient behaviors.

Most of the micro-scaled structures consist of rotating components. Thus, many researchers studied the rotary effects. Using spectral analysis, Murmu and Adhikari (2010) studied the wave scattering characteristic of a rotating single-walled carbon nanotube (SWCNT). Narendar and Gopalakrishnan (2011) modeled a Bernoulli–Euler rotating SWCNT beam using non-local theory.

The cantilever boundary condition has been of great interest among researchers recently. Challamel and Wang (2008) studied the bending of small scale rods using a simplified non-local beam theory. Moreover Lim, Li, and Yu (2009) studied nonlocal stress effect on a nanocantilever beam by taking into account the axial tortion. Many researchers studied the flapwise bending vibration of a rotating nanocantilever beam (Aranda-Ruiz et al., 2012, Narendar, 2012, Pradhan & Murmu, 2010). Also, recently, Ghadiri and Shafiei (2015) analyzed the nonlinear bending vibration of a rotating nanobeam for various boundary conditions using nonlocal Eringen's theory. Dehrouyeh-Semnani (2015) used the first deformation beam and modified couple stress theory to study size effect on flapwise vibration of rotating microbeams. Also, the rotary effect has been analyzed in some researches for clamp-simply supported (propped cantilever) boundary condition (Murmu & Adhikari, 2010, Narendar & Gopalakrishnan, 2011).

Static and dynamic analysis of uniform and non-uniform microbeams have been the focus of many papers. Lately, many researchers compared modified couple stress theory with other theories such as Eringen's nonlocal elasticity and classical (Abbasnejad, Rezazadeh, & Shabani, 2013, Dai, Wang, & Wang, 2015, Farokhi & Ghayesh, 2015, Miandoab, Pishkenari, Yousefi-Koma, & Hoorzad, 2014, Mohammad-Abadi & Daneshmehr, 2015, Mohammad-Abadi & Daneshmehr, 2014, Mohammadabadi, Daneshmehr, & Homayounfard, 2015). Chen, Li, and Xu (2011) analyzed bending of composite laminated beams by developing a modified couple stress model. Using the same theory, Reddy (2011) investigated the scale parameter effects on static bending, vibration and buckling of nonlinear Euler–Bernoulli and Timoshenko FG microbeams. Nateghi and Salamat-talab (2013) employed modified couple stress theory in conjunction with classical and first order shear deformation beam theories to study thermal and size effects on FG microbeams. Akgöz and Civalek (2011, 2013) used the modified strain gradient elasticity and modified couple stress theories to study bending and vibration behavior of AFG tapered Euler-Bernoulli microbeams with different boundary conditions. They also studied vibration response of non-homogenous and non-uniform microbeams with Bernoulli–Euler beam theory based on modified couple stress theory (Akgöz & Civalek, 2013), and buckling of linearly tapered micro-columns based on the modified strain gradient elasticity theory (Akgoz & Civalek, 2013). Asghari, Kahrobaiyan, and Ahmadian (2010) presented a nonlinear size-dependent Timoshenko beam model using the modified couple stress theory. Elishakoff and Guede (2004) studied vibration and buckling of simply supported axially graded beams. Park and Gao (2008) developed a micromechanics model for hexagonal honeycomb structures by using the modified couple stress theory and considering both bending and axial deformations of cell walls. They also presented an investigation of the longitudinal free vibration problem of a micro-scaled bar, using the strain gradient elasticity theory for clamped-clamped and clamped-free boundary conditions Akgöz and Civalek (2014).

In the present study, the transverse vibration of a rotary tapered AFG Euler–Bernoulli microbeam is studied based on modified couple stress theory by taking into account the axial forces due to the rotation, in the form of true spatial variation. The governing equations and boundary conditions are derived according to the Hamilton's principle and the governing equations are solved with the aid of the GDQEM. Parameteric study for the small-scale, the beam length and width, the rate of cross-section and nondimensional angular velocity on the vibration behavior of the non-uniform Euler-Bernoulli microbeam is presented for cantilever and propped cantilever boundary conditions. The vibrational behavior of AFG microbeam is also compared with pure metal and pure ceramic microbeams.

2. Formulation

2.1. Functionally graded materials

The problem of interest is a microbeam of length L, height '$h = h_1(1 + \beta_h x)$' and width '$b = b_1(1 + \beta_b x)$' that is rotating around x axis as shown in Fig. 1. Longitudinal and transversel cross sections are defined as $\beta_h = 1 - h_2/h_1$ and $\beta_b = 1 - b_2/b_1$ and the moment of cross-sectional area (I) and cross-sectional area (A) can be given as, respectively:

$$I(x) = \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} z^2 dydz \tag{1}$$

$$A(x) = \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} dydz \tag{2}$$

Considering Euler–Bernoulli AFG microbeam which is made by composing two different materials, i.e. metal and ceramic, the mechanical and geometrical properties of the microbeam are assumed to be varying along the axial direction (x) and it

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