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Nonlinear vibration of axially functionally graded non-uniform nanobeams

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ABSTRACT

In this paper, the nonlinear vibration analysis of axially functionally graded (AFG) non-uniform nanobeams is performed based on Eringen's nonlocal theory and Euler–Bernoulli beam model. Hamilton's principle is used to derive the equations with consideration of Von–Kármán's geometric nonlinearity. The boundary conditions are taken as simply supported, clamped and clamped-simply supported ends. The solution procedure for the nonlinear frequencies is done using homotopy perturbation method (HPM) in conjunction with the generalized differential quadrature (GDQ) method for the first time. The small parameter in homotopy perturbation method is derived by the linear solution using GDQ method. The frequencies of the nanobeams are examined for various parameters such as the nonlinear amplitude, AFG power index, nonlocal value, different boundary conditions and rates of cross section change along the thickness and for pure ceramic, AFG and pure metal nanobeams.

1. Introduction

The experimental results have shown disagreements between the classical continuum-based studies which proved that the classic theories are not strong tools for predicting the behavior of nanostructures accurately because they do not consider the internal length scale parameters makes. Thus, scientists have proposed a number of theories to define behavior of nano-systems, Mindlin and Tiersten (1962) and Yang, Chong, Lam, and Tong (2002). Using the vehicles of global balance laws and also the second law of thermodynamics, Eringen introduced the nonlocal field theory which expresses the behavior of a material in a point not only depends on that point, but also is dependent on the state of all other points in the body (Eringen & Edelen, 1972). Since then, Eringen's theory was employed to study micro and nano scaled structures for it includes the size parameters which are of significant importance in studying the small scaled materials.

Mindlin and Eshel (1968) introduced a strain gradient theory involved with five micro-scaled size dependent constants which is one of the first higher order continuum models. Fleck, Muller, Ashby, and Hutchinson (1994) used the dislocation theory to develop the rate independent plasticity strain gradient theory of. Moreover a strain gradient theory for elastic bending was proposed for plane-strain beams by Lam, Yang, Chong, Wang, and Tong (2003). Li, Li, and Hu (2016) studied the free vibration of size-dependent Timoshenko beams made of functionally graded material using the nonlocal strain gradient theory. Dynamic analysis of micro- and nano-structures has been the focus of many studies in the literatures. The mechanical behavior of a bimorph piezoelectric micro cantilever exposed to harmonic base excitation was investigated by

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Azizi, Ghodsi, Jafari, and Ghazavi (2016). Many researchers studied nanostructures, Chen, Li, Dai, and Qian (2014) studied the buckling and dynamic of a piezoelectric viscoelastic nanobeam. Murmu and Adhikari (2010) analyzed the vibration of double-nanobeam-systems. Zhang, Liu, and Wang (2004) developed a multiple shell model for the study of axial buckling of multi-walled carbon nanotubes under axial compression. The finite element formulations for the Euler–Bernoulli nanobeam and Kirchoff nanoplate are developed by Phadikar and Pradhan (2010) on the basis of nonlocal elasticity. Based on theory of nonlocal elasticity, Wang, Lu, and Lu (2007b) studied the buckling of multi-walled carbon nanotubes considering the uniform external radial pressure. Wang and Wang (2007) presented the constitutive relations of nonlocal elasticity theory to study the carbon nanotubes (CNTs) modeled as Euler–Bernoulli beam. Murmu and Pradhan (2009) studied the stability response of single walled carbon nanotube (SWCNT) embedded in an elastic medium using Timoshenko beam theory. Ansari, Mohammadi, Shojaei, Gholami, and Sahmani (2014b) investigated a modified continuum model to study the post-buckling deflection of nanobeams considering the effect of surface stress. Lei, Adhikari, and Friswell (2013) studied the dynamic behavior of nonlocal viscoelastic damped nanobeams. Li, Yao, Chen, and Li (2015) derived the governing equation of nanobeams on the basis of the two-dimensional differential constitutive relations of nonlocal elasticity in the plane-stress state. Shaat and Abdelkefi (2015) studied the effects of the material structure on the pull-in instability of nano-actuated beams made of nanocrystalline silicon (Nc–Si). The effects of surface energies on the nonlinear behavior of nanobeams were studied by Fu, Zhang, and Jiang (2010). The buckling of a SWCNT on Winkler foundation was studied by Pradhan and Reddy (2011) using differential transformation method. Zarepour, Hosseini, and Kokaba (2016) studied the electro-thermo-mechanical nonlinear vibration of nanobeam resting on the Winkler–Pasternak foundation. The nonlinear vibration of the piezoelectric nanobeams was studied by Ke, Wang, and Wang (2012a) on the basis of nonlocal theory and Timoshenko beam model. Afterwards, Emam (2013) presented a unified model for the nonlocal analysis of buckling and postbuckling states of nanobeams. Malekzadeh and Shojaee (2013) studied the surface effects on the nonlinear flexural free vibrations of elastically supported non-uniform nanobeams. The nonlinear free vibration of Timoshenko nanobeams with different types of end conditions is investigated by Ansari, Mohammadi, Shojaei, Gholami, and Rouhi (2014a) and the nonlinear forced vibration behavior of third-order shear deformable nanobeams was studied by Sahmani, Bahrami, Aghdam, and Ansari (2014). Ansari, Gholami, and Rouhi (2015a) developed a nonlocal geometrically nonlinear beam model to study the magneto-electro-thermo-elastic (METE) nanobeams under different conditions. Arani, Abdollahian, and Kolahchi (2015) studied the nonlinear vibration of a nanobeam coupled with a piezoelectric nanobeam based on the strain gradient theory. Considering electrostatic actuation, Fakhrabadi and Yang (2015) examined the nonlinear electromechanical behavior of nanobeams. The free vibration of third-order shear deformable functionally graded (FG) nanobeams around the post-buckling domain was investigated by Sahmani, Aghdam, and Bahrami (2015) based on an efficient numerical solution methodology. Nonlinear free vibration of simply-supported Euler–Bernoulli nanobeams with surface effects was analyzed by Hosseini-Hashemi, Nazemnezhad, and Rokni (2015). Most recently, Ansari, Oskouie, and Gholami (2016) developed a nonlinear fractional nonlocal Euler–Bernoulli beam model for the nonlinear analysis of size-dependent free vibration of fractional viscoelastic nanobeams. Vibration of Timoshenko FG nanobeam was discussed by Rahmani and Pedram (2014) considering the size-dependency effects.

FG materials which have continuously changing volume fractions of the constituents along a direction were first proposed in 1984 as the new generation of materials with vast applications. Studies on the FG nanobeams are complex due to the varying mechanical behavior along the structure and researchers have tried to derive the best theories to study FG beams. Chakraborty, Gopalakrishnan, and Reddy (2003) presented a beam element to examine the thermo-elastic behavior of FG beams and a new approach was proposed by Li (2008) for analyzing the static and dynamic behaviors of FG beams considering the rotary inertia and shear deformation. Also, high-order flexural theories were proposed by Benatta, Mechab, Tounsi, and Bedia (2008) for short FG symmetric beams under three-point bending.

Due to the vast applications of FG structures, a lot of researchers have studied different FG beams in recent years. The free vibration analysis of FG beam was performed by Aydogdu and Taskin (2007) considering the simply supported ends. Khalili, Jafari, and Eftekhari (2010) developed a method to study the dynamic of FG Euler–Bernoulli beams subjected to moving loads. Also, the bending and buckling behavior of FG nanobeams were studied by Şimşek and Yurtcu (2013). Nejad, Hadi, and Rastgoo (2016) , , studied the buckling of the nano-beams made of two-directional functionally graded materials (FGM) based on the nonlocal elasticity theory, with small scale effects.

Recently, a number of researchers made attempts to study the nonlinear behavior of FG structures. Şimşek (2010) studied the non-linear dynamic of a FG beam considering a moving harmonic load. Kocaturk, Şimşek, and Akbaş (2011) performed an investigation on the non-linear static behavior of a cantilever Timoshenko FG beam under a transversal uniformly distributed load. Based on finite element method, Eltaher, Emam, and Mahmoud (2012) studied the size-dependent free vibration of FG nanobeams. Nonlinear free vibrations of FG nanobeams considering surface effects were studied by Hosseini-Hashemi and Nazemnezhad (2013) and Sharabiani and Yazdi (2013). The free vibration of nonlinear material graduations of a nanobeam was investigated by Eltaher, Abdelrahman, Al-Nabawy, Khater, and Mansour (2014) based on the nonlocal Timoshenko theory and using finite element method. Hosseini-Hashemi, Nazemnezhad, and Bedroud (2014) studied the surface effects on the nonlinear free vibration of simply-supported functionally graded Euler–Bernoulli nanobeams using nonlocal elasticity. Niknam, Fallah, and Aghdam (2014) studied the non-linear bending of tapered FG beam considering thermal and mechanical loads. Nonlocal nonlinear vibration of nanobeams made of FGM are studied by Nazemnezhad and Hosseini-Hashemi (2014) and El-Borgi, Fernandes, and Reddy (2015). Kurtaran (2015) studied the large displacement static and transient behavior of FG curved beams. Şimşek (2016) studied the size-dependent nonlinear free vibration of a