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On size-dependent nonlinear vibration of porous and imperfect functionally graded tapered microbeams

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ABSTRACT

In current study, for the first time, the size dependent nonlinear vibration behavior of imperfect uniform and non-uniform functionally graded (FG) microbeams is investigated based on modified couple stress and Euler–Bernoulli theories. Due to difficulty of solving governing nonlinear differential equations of uniform and especially non-uniform microbeams, a few number of authors have studied nonlinear vibration of mechanical structures. It is assumed that a microbeam is made of FG material and for investigating the material properties, two types of porous distributions in a microbeam cross section area are considered. The governing differential equations are obtained using Hamilton's principle and considering the Von-Kármán's nonlinear strain. A generalized differential quadrature method (GDQM) and direct iterative method are presented to obtain the numerical results for the microbeam with simply and clamped edges through three boundary conditions. The influence of changes in some parameters such as nonlinear amplitude, material length scale, rate of thickness, FG index and porosity volume fraction on fundamental normalized frequency is studied and validity of the results is studied by several numerical examples.

1. Introduction

The FGM was presented by a group of Japanese scientists that were working on using composite materials in high temperature applications in the mid-1980s. The FG materials are a special type of composite materials made of two or more different materials that their composition and the structure regularly change with volume. The mechanical and physical properties of materials vary continuously along a specific direction that causes the smoothly change of volume fraction of materials. The FGMs have many applications in various fields such as biomechanics, nuclear energy, optics, aerospace, chemical plant, electronics, energy conversion, commodities and etc. (Mortensen & Suresh, 1995, Pompe et al., 2003, Rasheedat, 2012, Y. Miyamoto, Rabin, Kawasaki, & Ford, 1999).

Porosity is one of important parameters that are taken into consideration in many studies. There are some researchers that have worked on linear static and dynamic modeling of imperfect beams with porosity. Wattanasakulpong and Chaikittiratana (2015) utilized chebyshev collocation method to analyze flexural vibration of an imperfect FG Timoshenko beam using various boundary conditions. Two different types of porosity distributions were presented in their study. They deduced from the calculated results that even distribution of porosities has more significant influence on natural frequencies of FG beams in comparison with uneven porosity distribution. Chen, Yang, and Kitipornchai (2015) employed Hamilton's principle and Ritz method to study elastic buckling and static bending of a shear deformable FG Timoshenko porous beam

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with four different boundary conditions. Also in their analysis, in order to define the porous impact on developed equations; they considered two different porous distribution patterns.

Some researchers investigated nonlinear vibration of FG porous beams using different methods. Ebrahimi and Zia (2015) presented large-amplitude nonlinear vibration of FG Timoshenko beams made of porous materials solved Galerkin and multiple scales methods. They studied the effect of several parameters such as distribution profile, porosity volume fraction and etc. on natural frequencies of the FG porous beams. Furthermore, Wattanasakulpong and Ungbhakorn (2014) developed a differential transform method (DTM) to solve linear and nonlinear vibration of FG beam with porosities and different kinds of elastic supports. They concluded that, the ratio of the nonlinear frequency to the linear frequency increases with increasing the volume fraction of porosity.

In addition, there are many authors that have studied nonlinear static and dynamic behavior of geometrically imperfect beams and microbeams (Farokhi & Ghayesh, 2015, Farokhi, Ghayesh, & Amabili, 2013, Ghayesh & Amabili, 2014, Shafiei, Kazemi, & Fatahi, 2015, Shafiei, Kazemi, & Ghadiri, 2015, Yaghoobi & Torabi, 2013).

Nowadays, micro-electro-mechanical systems (MEMS) are widely applied in different industries including bio-mechanics, aerospace, telecom, IT and etc. (Li, Bhushan, Takashima, Baek, & Kim, 2003, Pei, Tian, & Thundat, 2004, Vytautas Ostasevicius, 2011). Huge application potentials of these systems cause that many researchers work on dynamic and static modeling of different types of micro-/nano systems such as micro-/nano-plates and micro-/nano-beams (Akgöz & Civalek, 2014, Dehrouyeh-Semnani, 2014, Dehrouyeh-Semnani, 2015a, Dehrouyeh-Semnani, 2015b, Dehrouyeh-Semnani, Behboodijouybari, & Dehrouyeh, 2016, Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015a, Dehrouyeh-Semnani, Dehrouyeh, Zafari-Koloukhi, & Ghamami, 2015b, El-Borgi, Fernandes, & Reddy, 2015, Fakhrabadi, Rastgoo, & AHMADIAN, 2014, Ghadiri & Shafiei, 2016, Ghayesh, Farokhi, & Alici, 2015, Lim, Yang, & Zhang, 2012, Mohammad Abadi & Daneshmehr, 2014a, 2014b, Mohammadabadi, Daneshmehr, & Homayounfard, 2015, Reddy, El-Borgi, & Romanoff, 2014, Sedighi, Koochi, Daneshmand, & Abadyan, 2015, Shafiei, Kazemi, & Ghadiri, 2016a, 2016b, Shafiei, Mousavi, & Ghadiri, 2016, Taati, 2016, Tang, Ni, Wang, Luo, & Wang, 2014, Wang and Li, 2014). Due to inability of classical theories to model size dependent behavior of micro-scale structures, some researchers presented several non-classical theories. Strain gradient, modified strain gradient, couple stress and modify couple stress theories were popular non-classical approaches that many researchers utilized to study statics and dynamics of micro-scale beams and plates. Among different approaches, the modify couple stress is very popular because of its accuracy and matching the results with experimental data. A large number of authors have developed a modified couple stress theory for modeling the behavior of materials in micro scale. Dai, Wang, and Wang (2015) worked on nonlinear dynamic cantilevered microbeams based on the modified couple stress theory. They found out that with adding a linear spring to a cantilevered microbeam subjected to harmonic base excitations, resonance frequency increases and resonance amplitudes decreases. Reddy (2011) utilized the modified couple stress theory to analyze nonlinear Euler–Bernoulli and FG Timoshenko microbeam. He investigated the influence of scale parameter on static bending, vibration and buckling. Ghayesh, Amabili, and Farokhi (2013) investigated geometrically nonlinear size-dependent behavior of a Timoshenko microbeam with Galerkin technique. In their article, two modified couple stress and classical theories have been compared. Also, the modified couple stress theory in a most number of researches has been applied (Akgöz & Civalek, 2014, Dehrouyeh-Semnani et al., 2015b, 2016, Ghayesh et al., 2015, Jia, Ke, Feng, Yang, & Kitipornchai, 2015, Ke, Wang, Yang, & Kitipornchai, 2012, Mohammad Abadi & Daneshmehr, 2014a, 2014b, Mohammadabadi et al., 2015, Şimşek, 2014, Şimşek, 2015, Taati, 2016, Tang et al., 2014).

As it is seen in the literature, no research effort has been devoted to analyze nonlinear vibration behavior of porous uniform and non-uniform FG microbeams based on the modified couple stress theory so far. Therefore, in this study, the size dependent nonlinear vibration behavior of Euler–Bernoulli FG microbeam made of porous material is presented. It is considered that the FG microbeam is made of ceramic and metal; also, properties of materials vary throughout the thickness (z direction) according to the power law. The modified couple stress theory has been utilized to investigate material behaviors at micro scale. Governing equations and boundary conditions are derived from Hamilton's principle and the GDQM is utilized to solve derived micro-dimensional equations for simply supported-simply supported (SS), simply supported-clamped supported (SC) and clamped supported –clamped supported (CC) microbeams. The increasing or decreasing effects of some important parameters such as nonlinear amplitude, material length scale, porosity volume fraction and FG index on the values of frequencies are studied. The accuracy and validity of the results are shown through several numerical examples. The results of this article can be a good reference for designing and optimizing the elastic MEMSs.

2. Modeling

Considering a FG Euler–Bernoulli microbeam which is made of two different material compositions; the physical and mechanical properties of the microbeam are assumed to vary through the thickness (along z axis) (Fig. 1). This variation in properties can be defined as the power law which is presented as follows.

$$V_1(z) = \left(\frac{z}{h} + \frac{1}{2}\right)^n \tag{1}$$

$$V_2(z) = 1 - V_1(z) \tag{2}$$

where, the subscripts 1 and 2 denote ceramic and metal which were applied in FG microbeam (Fig. 1).