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Analysis and modeling the size effect on vibration of functionally graded nanobeams based on nonlocal Timoshenko beam theory

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ABSTRACT

In this study Timoshenko beam theory that applies the size dependent effects in functionally graded material (FGM) beam is discussed. The material properties of FG nanobeams are considered to vary over the thickness based to the power law. The equations of motion according to Eringen nonlocal theory, using Hamilton's principle are derived and a closed-form solution is presented for vibration behavior of the proposed model. The nonlocal elasticity theory contains a material length scale parameter that can apply the size effect in a FG material. The model is verified by comparing the obtained results with benchmark results available in the literature. In following a parametric study is accompanied to examine the effects of the gradient index, length scale parameter and length-to-thickness ratio on the vibration of FGM nanobeams. It is observed that these parameters are vital in investigation of the free vibration of a FG nanobeam.

1. Introduction

A functionally graded material (FGM) is described by a continuous material variant in one or more dimensions by steadily changing the microstructure from one material to another for the optimum distribution of component materials. FGMs present numerous profits (Byrd & Birman, 2007) containing improved stress spreading, enhanced thermal resistance, higher fracture toughness, and inferior stress intensity factors that introduce them very eye-catching choice in various engineering fields. This category of materials affords the specific profits of both ingredients. The continuously compositional variation of the constituents in FGMs from one surface to the other offers an elegant solution to the problem of appearing high shear stresses that may be induced in laminated composites, where two materials with great differences in properties are joined (Asghari, Ahmadian, Kahrobaiyan, & Rahaeifard, 2010; Bhangale, Ganesan, & Padmanabhan, 2006). Actually, material gradation will reduce maximum stresses and change the spatial location where such maximums arise. This provides the opportunity of fitting material variation to attain desired stresses in a structure. The inspiration for using functionally graded materials (FGMs) is their advantages of superior stress relaxation and abilities of enduring high temperature gradients. The ceramic part of the material delivers the high temperature resistance due to its low thermal conductivity. The ductile metal part avoids fracture produced by stresses owing to high temperature gradient in a very short period of time (Şimşek, 2010). The mechanical and thermal reaction of FG materials is of extensive concentration in several technological areas such as biomechanics, optoelectronics, high temperature technology and nanotechnology. They are also perfect for reducing thermomechanical incompatibility in metal–ceramic bonding. Gradations in microstructure are also usually found in biological

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cellular materials, where biological adaptation has dispersed the strongest microstructure in regions that experience the highest stress (Khanchehgardan, Rezazadeh, & Shabani, 2013).

With the quick growth of nanostructures, FGMs are extensively used in micro- and nano-structures such as thin films (Craciunescu & Wuttig, 2003; Fu, Du, & Zhang, 2003, 2004; Lee et al., 2006; Lü, Chen, & Lim, 2009; Lü, Lim, & Chen, 2009; Mahmud, Liu, & Nam, 2007, 2008; Meng, Liu, Yang, Shariat, & Nam, 2012; Miyazaki, Fu, & Huang, 2009; Shariat, Liu, & Rio, 2013; Shariat, Liu, & Rio, 2013), microswitches (Jia, Yang, & Kitipornchai, 2010, 2011; Jia, Yang, Kitipornchai, & Lim, 2010; Shariat, Liu, & Rio, 2012; Shariat, Liu, Meng, & Rio, 2013), micro piezoactuator (Carbonari, Silva, & Paulino, 2009), and micro/nano-electromechanical systems (MEMS and NEMS) (Batra, Porfiri, & Spinello, 2008; Chen, Zhang, Richardson, & Luo, 2008; Hasanyan, Batra, & Harutyunyan, 2008; Jia, Yang, Kitipornchai, & Lim, 2012; Lun, Zhang, Gao, & Jia, 2006; Mohammadi-Alasti, Rezazadeh, Borgheei, Minaei, & Habibifar, 2011; Moser & Gijs, 2007; Witvrouw & Mehta, 2005; Zhang & Fu, 2012). Jia, Yang, Kitipornchai, and Lim (2011) investigated the forced vibration of non-homogeneous FG micro-switches under combined electrostaticc, intermolecular forces and axial residual stress. In this study the effects of material composition, gap ratio, slenderness ratio, intermolecular force, axial residual stress on the pull-in instability were shown. In another study, they investigated the nonlinear pull-in characteristics of the microswitches made of either homogeneous material or non-homogeneous functionally graded material (FGM) with two material phases under the combined electrostatic and intermolecular Casimir force (Jia et al., 2010). As it is challenging for a single layer to encounter all material and economical necessities pretended to an MEMS structural layer, Witvrouw and Mehta (2005) recommended the use of a non-homogenous functionally graded material layer, to attain the favorite mechanical and electrical properties. Fine-tuning of the stress gradient was achieved by the use of a top stress compensation layer, whose optimum thickness was estimated from an assessment of the stress gradient shape through thickness.

Carbonari et al. (2009) developed the idea of functionally graded materials and multifunctional by adapting piezoelectric and elastic properties of the piezoceramics to obtain improved micro-tool performance. Micro/Nano-tools offer significant promise in a wide range of applications such as cell manipulation, microsurgery, and nanotechnology processes. Such special tools consist of multi-flexible structures actuated by two or more piezoceramic devices that must generate output displacements and forces at different specified points of the domain and at different directions. The design of these micro/nano-tools involves minimization of the coupling among movements generated by various piezoceramics. To obtain enhanced tool performance, the concept of multifunctional and functionally graded materials is extended by tailoring elastic and piezoelectric properties of the piezoceramics. The design process considers the influence of piezoceramic property gradation. In the following they considered the design of a single piezoactuator, an XY nano-positioner actuated by two graded piezoceramics, and a micro-gripper actuated by three graded piezoceramics. The results show that material gradation plays an important role to improve actuator performance, which may also lead to optimal displacements and coupling ratios with reduced amount of piezoelectric material (Carbonari et al., 2009). Hasanyan et al. (2008) investigated the pull-in instabilities in a functionally graded MEMS according to the heat created by the electric current. The material properties of the two-phase MEMS are presumed to vary continuously in the thickness. It was shown that the pull-in voltage strongly depends upon the variation through the thickness of the volume fractions of the two constituents. Rahaeifard, Kahrobaiyan, and Ahmadian (2009) suggested an enhanced FGM micro cantilever beam to improve the atomic force microscopes sensitivity. According to the characteristic size of beams used in MEMS and NEMS the small-scale-effect in their behavior is significant.

Fu, Du, Huang, Zhang, and Hu (2004) in their review paper, argued serious subjects and problems in the growth of TiNi thin films, including characterization and preparation considerations, frequency improvement, residual stress and adhesion, fatigue and stability, modeling the functionally graded or composite thin films. To further improve the properties of TiNi films functionally graded TiNi-based films can be designed. So far, there are different design models for the functionally graded TiNi thin films. The first type is through the gradual change in composition (Ti/Ni ratio), crystalline structures, transformation temperatures, and/or residual stress through film thickness (Quandt et al., 1996; Takabayashi et al., 1996). As the Ti or Ni content changes in the film, the material properties could change from pseudo-elastic to shape memory. The seamless integration of pseudo-elastic with shape memory characteristics produces a two-way reversible actuation, because residual stress variations in thickness will enable biasing force to be built inside the thin film. In order to improve biocompatibility and adhesion of TiNi films, a functionally graded Ti/TiNi/Ti/Si graded layer could be proposed. A thin layer of surface Ti layer can improve biocompatibility (prevent potential Ni allergic reactions), while the Ti interlayer is used to improve film adhesion. Other functionally graded designs include the combination of TiNi films with piezoelectric, ferromagnetic, or magnetostrictive thin films (Craciunescu & Wuttig, 2003). Response time of the piezoelectricity mechanisms (PZT films) is fast, but the displacement is relatively small. TiNi film, on the other hand, has a large force–displacement, but with slow response frequency. By coupling TiNi and PZT films to fabricate a new hybrid hetero structure composite or functionally graded films, it is possible to tune or tailor the static and dynamic properties of TiNi thin films, which may generate a larger displacement than conventional piezoelectric or magnetrostrictive thin films and have an improved dynamic response compared with that of single layer TiNi films (Fu et al., 2004).

For structures with submicron sizes, due to the increasing surface-to-bulk ratio, surface effects are likely to be significant and can considerably modify macroscopic properties (Cammarata, 1994; Müller & Saúl, 2004). It is known that there exists a size-dependent mechanical response of nano-scale structures (Cammarata & Sieradzki, 1989; Miller & Shenoy, 2000; Wolf, 1991). Atomistic simulations results have shown that elastic constants of nano structures can be larger or smaller than their bulk counter-parts due to the effect of surface energy (Shim, Zhou, Huang, & Cale, 2005; Zhou & Huang, 2004). In addition, the atomistic lattice model further demonstrates that the values of elastic constants of nano structures are thickness