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On vibrations of porous nanotubes

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ABSTRACT

In this study, the vibration behaviors of porous nanotubes are investigated for the first time. The nonlocal strain gradient theory in conjunction with a refined beam model are employed to formulate the size-dependent model. It is presumed that the porous nanotubes are made from functionally graded materials, and the material parameters of nanotubes relate to temperature variation and vary continuously in the radial direction. Employing a refined beam theory which includes the effects of transverse shear deformation, the equations of motion are derived based on Hamilton's variation principle and solved by the Navier solution method. Some comparisons are presented to valid the correctness of present solution method. The effects of the nonlocal parameter, strain gradient parameter, temperature variations, porosity volume fraction and material variation on the vibration characteristic of the nanotubes are discussed in detail.

1. Introduction

Nanostructures have special, size-dependent properties. It was shown by experimental investigations and atomistic simulations that some remarkable size-dependent effects could be observed on nanostructures. It means that when the external dimension or volume of structures changes into nano-scale, the size effect, which can be neglected in macro size, become significant and must be considered in nano- or micro- scale structures (Demir & Civalek 2017; Li, Li, Hu, Ding, & Deng, 2017). Since the classical continuum theory is unable to appropriately explain the new mechanical phenomena at nano scale due to the lack of size effect in constitutive equation, several non-classical theories have been proposed, such as nonlocal elasticity theory (Eringen, 1983), strain gradient theory (Mindlin, 1965), and nonlocal strain gradient theory (Lim, Zhang, & Reddy, 2015).

The nonlocal elasticity theory implies the stress at a reference point in a body is determined by not only the strain at that point, but also the strains at all other point of the body. This theoretical hypothesis could reasonably explain some phenomena associated with atomic scale (Li, Wang, & Mai, 2008) and can be used to simulate the mechanical behavior of nanostructures (Ebrahimi & Salari, 2015a, b, c; Eltaher, Khater, & Emam, 2016; Fernández-Sáez, Zaera, Loya, & Reddy, 2016; Mohamed, Shanab, & Seddek, 2016; Nejad, Hadi, & Rastgoo, 2016; Nejad and Hadi, 2016a, b; Barati, 2017a; Ghadiri, Rajabpour, & Akbarshahi, 2017; Karličić, Kozić, & Pavlović, 2016; Rahmani & Pedram, 2014; Shafiei, Kazemi, & Ghadiri, 2016a, b,c; Shafiei, Kazemi, Safi, & Ghadiri, 2016; Shafiei, Mirjavadi, Afshari, Rabby, & Hamouda, 2017; Shen, 2011; Şimşek, 2014; Şimşek & Yurtcu, 2013; Thai & Vo, 2012; Thai, Thai, Vo, & Patel, 2018; Tuna & Kirca, 2016a, b, 2017; Xu, Deng, Zhang, & Xu, 2016). However, the Eringen's model which only incorporates the stiffness softening effect, could not be used for accurate description of the stiffness-hardening effect in many research works (Fleck & Hutchinson, 1993; Lu, Guo, & Zhao, 2017a, b).

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The strain gradient theory advanced by Mindlin (1965) is another size-dependent continuum theory, and this theory contains 16 additional independent higher-order material constants. Because of the complexity of the Mindlin's theory, the analytical solution is quite difficult to obtain. Consequently its application is rather restricted within a narrow circle. To compensate for this, a series of studies were performed to reduce the additional parameters. For instance, Lam, Yang, Chong, Wang, and Tong (2003) put forward a modified strain gradient theory including three length scale parameters. Further, Yang, Chong, Lam, and Tong (2002) proposed the modified couple stress theory which incorporates only one length scale parameter. Within the framework of these theories, Akgöz and Civalek (2013, 2014) studied the vibration (2013) and thermal-buckling (2014) of nanobeams by the sinusoidal beam model (Touratier, 1991). Khorshidi, Shariati, and Emam (2016), discussed the postbuckling behavior of nanobeam using various beam theories. Many relevant research works have been carried out (e.g. Dehrouyeh-Semnani, Dehrouyeh, Zafari-Koloukhi, & Ghamami, 2015; Al-Basyouni, Tounsi, & Mahmoud, 2015; Attia, 2017; Attia, & Mohamed, 2017; Dehrouyeh-Semnani & Bahrami, 2016; Luan, Nguyen, Vo, & Nguyen, 2016; Mohammad-Abadi & Daneshmehr, 2014; Shafiei et al., 2016a, b; Şimşek & Reddy, 2013; Taati, 2016; Xu & Deng, 2016) and indicate that the models incorporate the stiffness enhancement effect.

Obviously, from the discussions above, Eringen's theory and the strain gradient theory are two different non-classical theories and incorporate two different scaling effects. To combine and associate the two size-dependent effects, Lim et al. (2015) proposed a nonlocal strain gradient theory which bridges Eringen's theory and the strain gradient theory. In addition, it has confirmed that there exists noticeable consistency between molecular dynamics simulations and theoretical studies for the wave propagation behavior of CNTs. Since then, many works have tried to use this hypothesis to explain buckling and vibration behaviors of small-scaled structures (Barati, 2017a, b; Fernandes, El-Borgi, Mousavi, Reddy, & Mechmoum, 2017; Li & Hu, 2015; Li & Hu, 2016; Li, Li, & Hu, 2016; Barati, & Zenkour, 2017; Lu et al., 2017a, b; Xu, Zheng, & Wang, 2017). However, previous studies in this respect have only focused on the problems of buckling and vibration of the nano-scaled beams and plates.

On the other hand, functionally graded materials (FGMs) are a novel non-uniform composite materials, nowadays, FGM nanostructures are widely used in NEMS and MEMS due to the rapid developments in nanotechnology, many researches concerning mechanical behaviors of nanostructures are available in the literature (Ebrahimi & Barati, 2016, 2017a,b; Ebrahimi & Salari, 2015a,b,c; Nejad et al., 2016; Nejad and Hadi, 2016a, b; Akgöz & Civalek, 2013, 2014; Shafiei et al., 2016b,c; Şimşek & Yurtcu, 2013; Al-Basyouni et al., 2015; Li & Hu, 2016; Li et al., 2016; Şimşek, 2016; Şimşek & Reddy, 2013). Among these, Li and Hu (2015) advanced a size-dependent Euler–Bernoulli model based on the nonlocal strain gradient theory to study the buckling and postbuckling behavior of nanobeams, this work was then extended to the case of bending and vibration analysis of nanobeams (Li & Hu, 2016). Şimşek (2016) and Li et al. (2016) investigated the nonlinear vibration behavior of FGM nanobeams using the Euler–Bernoulli beam theory. Ebrahimi and Barati (2017a) discussed damping vibration behaviors of FGM nanobeams via a new refined beam theory. Besides, due to some reasons such as manufacture, porosity are easy to occur in FGM, which inevitably affect the mechanical property of FGM, so it is significant to study nanostructures with porosities. Some studies have considered this point (e.g. Chen, Yang, & Kitipornchai, 2015, 2016; Atmane, Tounsi, & Bernard, 2017; Atmane, Tounsi, Bernard, & Mahmoud, 2015; Ebrahimi & Zia, 2015; Hadji & Bedia, 2015; Hadji, Daouadji, & Bedia, 2015; Wang & Zu, 2017; Wattanasakulpong & Chaikittiratana, 2015; Wattanasakulpong & Ungbhakorn, 2014; Şimşek & Aydın, 2016; Benferhat, Daouadji, Hadji, & Mansour, 2016; Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015; Dehrouyeh-Semnani, Mostafaei, & Nikkhah-Bahrami, 2016; Galeban, Mojahedin, Taghavi, & Jabbari, 2016; Mechab, Mechab, Benaissa, Ameri, & Serier, 2016; Shafiei & Kazemi, 2017; Shafiei, Mousavi, & Ghadiri, 2016a,b). Among those, Wattanasakulpong, Prusty, Kelly, and Hoffman (2012) studied the free vibration of FGM beams and validated his results with experiment, they concluded that the porosity could change the vibration behavior of FGM beams. Ebrahimi and Barati (2017b), Ebrahimi and Zia (2015) and Ebrahimi, Ghasemi, and Salari (2016) studied the free vibration of FGM porous nanobeams and showed that the frequency increase as the volume fraction of porosity increases; and this conclusion has been supported by Hadji and Bedia (2015) and Hadji et al. (2015). But a recent study of the vibration of FGM porous nanobeams by Shafiei et al. (2016a,b) suggests that, with the increase of porosity volume fraction, the frequency can increase or decrease, depending on the value of power law index. Obviously, there are inconsistencies here, and it is this inconsistency that motivates us to study the influence of porosity on the vibration behavior of nanotubes.

For analysis of nanotubes, Hu, Song, Deng, Yin, and Wei (2017) used the Euler–Bernoulli beam model and the Eringen's theory to analyze the axial dynamic buckling of carbon nanotubes (CNTs). Kheibari and Beni (2016) coupled the thin shell model with modified strain gradient theory and investigated the vibration of piezoelectric nanotubes. Employing the Timoshenko beam theory and the Eringen's theory, Lei, Natsuki, Shi, and Ni (2012) discussed the vibration of double-walled nanotubes. Based on the Euler and Timoshenko beam model, Lim et al. (2015) examined the wave propagation of CNTs. Fu, Hong, and Wang (2006) and Liew and Wang (2007) investigated the vibration and wave propagation of CNTs via the beam and thick shell theories, respectively. Recently, based on the Laurent series expansion, a higher-order beam model for tubes is derived and proposed by Zhang and Fu (2013), the simulation results showed that the accuracy of this model is approximately equal to the moderately thick shell model and Timoshenko beam model. This conclusion has been supported by Fu, Zhong, Shao, and Chen (2015), Zhong, Fu, Wan, and Li (2016) and She, Yuan, and Ren (2017). Based on this tube model, She, Yuan, Ren, and Xiao (2017) presented buckling and postbuckling analysis of porous nanotubes. However, there is no research studying the vibration behavior of nanotubes using this model. Moreover, there is no studies investigating the vibration behavior of nanotubes with porosities.