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On wave propagation of porous nanotubes

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An analytic model of porous nanotubes for the wave propagation analysis is formulated with the help of the nonlocal strain gradient theory. The dispersion relations between phase velocity and wave number is determined by solving an eigenvalue problem. It is found that the asymptotic phase velocity can be increased by increasing the strain gradient parameter or decreasing the nonlocal parameter. In addition, the heterogeneity of functionally graded materials and temperature variation have a substantial influence on the dispersion relations of nanotubes. The nonlocal parameter and strain gradient parameter have significant effects on the dispersion relation at high wave numbers, in contrast, this effects can be negligible at low wave numbers. Meanwhile, it can be inferred that the phase velocity can decrease or increase as the porosity volume fraction rises, which depends on the power law index.

1. Introduction

Over the past two decades, nanotubes have attracted the attention of many researchers and have been widely applied in nano-electronics devices and nano-biological systems. Generally, nanotubes can be broadly classified into two categories, one is the carbon nanotube that is curled by a single layer of atoms, the other is nanotube made of metal (He et al., 2011; Lu et al., 2011), semiconductor, organics (Shimizu, 2008; Yang et al., 2007) and nano-fibers (Mccann, Li, & Xia, 2005) with hollow cross section. In fact, some other one-dimensional nanostructures with circular cross-section such as nanorods, nanowires Zhang (2011) and so on can also be regarded as special kinds of nanotubes, in that case, the inner diameter of the nanotubes is equal to zero. The results of experiments and atomistic simulations show that nanotubes have unique and size-dependent properties. Since the classical continuum theory is failed to account for the size effect, some researchers employed the nonlocal Euler beam (Hu, Song, Deng, Yin, & Wei, 2017; Wang, 2005), nonlocal Timoshenko beam model (Hu, Liew, & Wang, 2009) or nonlocal shell model (Kheibari & Beni, 2016) to study the flexural wave dispersion of nanotubes, while some others (e.g., Wang, Hu, & Guo, 2006) used the strain gradient theory to formulate the size-dependent model. Besides, Kheibari and Beni (2016) used the consistent couple stress theory (Hadjesfandiari, 2013) and the thin shell model to perform the vibrational analysis of piezoelectric nanotubes, their study revealed that, the size effects, electromechanical effects, and geometric effects can change the vibration behavior of piezoelectric nanotubes. And Song, Shen and Li (2010) coupled a new hypothesis including two scaling parameters with the Euler–Bernoulli beam theory and studied the dispersion relation of waves propagating in nanotubes, they obtained the expression of the phase and group velocities, and investigated the effects of initial axial loading on the wave velocity.

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Recently, Lim, Zhang, and Reddy (2015) developed a new higher-order nonlocal strain gradient elasticity system which takes the higher-order stress gradients and strain gradient nonlocality into account. This theory is distinctive because the classical nonlocal stress theory (Eringen, 1983) does not incorporate the nonlocality of higher-order stresses while the common strain gradient theory (Aifantis, 1992; Mindlin, 1965) only considers local higher-order strain gradients without nonlocal effects. To illustrate its application values, they employed the Euler and Timoshenko beam theories to discuss the wave propagation in nanotubes. They pointed out, unlike the prevalent nonlocal stress model, this new model can predict stiffness hardening effect for very large wave length with the presence of the nonlocal strain gradients. This conclusions have also been confirmed by the many related works (e.g. Barati, 2017; Barati, & Zenkour, 2017; Dehrouyeh-Semnani, 2017; Ebrahimi & Barati, 2016; Ebrahimi, Barati, & Dabbagh, 2016; Ebrahimi, Daman, & Jafari, 2017; Ghayesh, Farokhi, & Gholipour, 2017; Hadi, Nejad, & Hosseini, 2018; Karami, Janghorban, & Tounsi, 2017; Karami, Shahsavari, & Li, 2018; Li, Hu, & Ling, 2015; Li, Li, & Hu, 2016; Li, Li, Hu, Ding, & Deng, 2017; Li, Tang, & Hu, 2018; Lu, Guo, & Zhao, 2017; Lu, Guo, & Zhao, 2018; Rajasekaran, & Khaniki, 2017; Romano, & Barretta, 2017; Sahmani, Aghdam, & Rabczuk, 2018; Shahverdi, & Barati, 2017; Shen, Chen, & Li, 2016; Şimşek, 2016; Xu, Wang, Zheng, & Ma, 2016; Xu, Zheng, & Wang, 2017; Zhu & Li, 2017a,b).

On the other hand, owing to their outstanding properties such as high surface area, controllable pore volume, and various chemical compositions, porous nanomaterials have exhibited promising applications in the field of sorption, catalysis, sensing, optics, magnetics, biomedicine and electrochemistry (Zhao et al., 2013; Zou et al. 2015; Zou et al., 2016). Porous nanotubes, which combine the advantages of nanotubes and porous nanomaterials, are considered to be one of the most important porous nanostructures. Compared with the other porous nanostructures, the porous nanotubes have much higher electrical conductivity, surface area and energy and so on (Tang et al., 2018). Some researchers are devoted to studying the properties of porous nanotubes and indicate that porous nanotubes have tremendous developing potentiality and significant application value. For example, He et al. (2011) suggested that the light to electric energy conversion efficiency of the dye-sensitized solar cells (DSSCs) applying porous TiO_2 nanotubes is nearly two times higher than that of the DSSCs based on normal TiO_2 nanotubes. Wei et al. (2017) suggested that porous nanostructures and porous nanotubes can overcome the limitations of many electrode materials, so that high capacity, fast charge and discharge, and long cycle life can be realized. Wang, Song, Yu, and Gu (2016) reported the formation mechanism of meso–porous silica shells (MSS) on single-walled carbon nanotubes (SWCNTs) and indicated that this new porous functional nanomaterial has huge potential use in cancer treatment. Du et al. (2010) proposed a new and simple method to synthesizing the porous Co_3O_4 nanotubes with the diameter of about 30 nm, and indicated that the porous nanotubes exhibit the superior li-battery performance with good cycle life and high capacity. Wang et al. (2015) investigated the mechanism for the formation of the porous Fe_2O_3 nanotubes and shown that porous Fe_2O_3 nanotubes exhibit good lithium storage performance with high specific capacity and good cycling stability. Bucior, Chen, Liu, and Johnson (2016) indicated that the porous nanotubes can effectively separate gas mixtures with high selectivity and high permeance. Guo et al. (2018) successfully synthesized the mono-disperse Ho_2O_3 –Fe_2O_3 porous nanotubes, and demonstrated that the Ho_2O_3 –Fe_2O_3 porous nanotubes has a promising application for detecting acetone. Li (2016) studied the effect of porosity on pore microstructure of magnesium/carbon nanotube and indicated that the total specific surface area increases significantly with the increase of overall porosity. Yzeiri and Patra (2014) studied the fluidic properties of porous carbon nanotubes by molecular dynamics simulations and suggested that the porous carbon nanotubes can be used as selective molecular sieves. Wan et al. (2015) indicated that Ag_3PO_4 porous nanotubes not only exhibit the highest adsorption ability towards dye molecules, but also possess superior photocatalytic activity than that of Ag_2CO_3 nanorods, and the origin of the higher photocatalytic activity is primarily ascribed to the peculiar porous tubular nanostructure.

On the contrary, the mechanical behavior of porous nanotubes under mechanical loading or thermal loadings still have not been studied systematically. At present, only very limited researches were carried out in this area. Based on the nonlocal stress theory, She, Yuan, Ren, and Xiao (2017) performed buckling and postbuckling analysis of porous nanotubes made of functionally graded materials, they pointed out that the presence of porosity volume fraction can increase the buckling temperature and post-buckling strength of porous nanotubes. This work was then extended to the case of the vibration of porous nanotubes by the same authors (She, Ren, Yuan, & Xiao, 2018). In their work, they suggested that, the presence of porosity can increase the frequency of nanotubes, but also can decrease the frequency of nanotubes. However, as a more common problem and a more difficult problem, the study of wave propagation of porous nanotubes does not get any attention. It is this fact that motivates us to study the wave propagation of porous nanotubes.

In this paper, the wave propagations of porous nanotubes are investigated for the first time. The porosity-dependent and size-dependent model is established via the nonlocal strain gradient theory. The results of the Euler-Bernoulli beam, Timoshenko beam and three-dimensional elasticity solution are also presented and compared. Detailed parametric studies are performed to investigate the effects of the scaling parameters, porosity volume fraction, temperature variation and material variation on the wave propagation characteristics of porous nanotubes.

2. Material properties

Consider a porous nanotube made of functionally graded materials which consists of two different materials. The length, outer radius and inner radius of the nanotube are denoted by L,R_0 and R_i. The nanotube is referred to a coordinate system $O(x, y, z)$, in which x-axis is oriented in the neutral axis of the nanotube, the z-axis is directed upward and perpendicular to the x-axis, the origin of the coordinate system is located at the end of the nanotube on the middle plane, let u_1, u_2, and