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On wave propagation in nanoporous materials

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ABSTRACT

In this paper, a general bi-Helmholtz nonlocal strain-gradient elasticity model is developed for wave dispersion analysis of porous double-nanobeam systems in thermal environments. The present model incorporates three scale coefficients to examine wave dispersion relations much accurately. Porosity-dependent material properties of inhomogeneous nanobeams are defined via a modified power-law function. Based on Hamilton's principle, the governing equations of double-nanobeam system on elastic substrate are obtained. Solving analytically these equations gives wave frequencies and phase velocities as a function of wave number. It is demonstrated that phase velocities of a nanoporous double-nanobeam system rely on the porosities, thermal loading, material gradation, nonlocal parameters, strain gradient parameter, interlayer springs, elastic substrate and wave number.

1. Introduction

Recently, introducing new continuum theories for modeling of nanoscale structures has gained intense interest in order to describe the small size effects of such structures wherein the interactions of nonadjacent atoms are not ignorable. Most cited continuum mechanics for modeling of nanostructures is nonlocal theory introduced by Eringen (1983) in which long range forces between atoms are involved. In fact, this theory assumes that the stress of a given point in continuous body is associated with the strains of all points not only those near that given point. Due to possessing a material scale parameter, nonlocal elasticity theory has been broadly applied in analysis of nanoscale beams and plates (Barati, Zenkour, & Shahverdi, 2016; Ebrahimi & Barati, 2017a, 2016a, Fernández-Sáez, Zaera, Loya, & Reddy, 2016; Nejad, Hadi, & Rastgoo, 2016; Pavlović, Karličić, Pavlović, Janevski, & Ćirić, 2016; Rahmani & Pedram, 2014; Sarkar & Reddy, 2016; Shafiei, Kazemi, Safi, & Ghadiri et al., 2016; SoltanRezaee & Afrashi, 2016; Tuna & Kirca, 2016; Zenkour & Abouelregal, 2016).

However, several researchers have been discussed on the limitations and inabilities of nonlocal elasticity theory. Romano, Barretta, Diaco, and de Sciarra (2017) examined the efficiency of differential form of nonlocal elastic law is predicting mechanical behaviors of nanobeams, especially those with clamped-free boundary conditions. They discussed on the inability of nonlocal differential elasticity in analysis of nano-cantilevers and proposed a solution for such problems. Koutsoumaris, Vogiatzis, Theodorou, and Tsamasphyros (2015) examined the application of bi-Helmholtz nonlocal elasticity model with two nonlocal parameters in vibration analysis of carbon nanotubes. By comparing obtained results with those of molecular dynamic (MD) simulation, they concluded that present bi-Helmholtz nonlocal elasticity in more appropriate than one parameter nonlocal elasticity in predicting mechanical behavior of nanostructures. Shaat and Abdelkefi (2017) have been proved that wave propagation curves of nanobeams cannot be verified with those of experimental data with only one nonlo-

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cal parameter. Therefore, they used a general nonlocal elasticity theory containing two nonlocal scale parameters to predict wave characteristics of nanobeams much accurately.

In the main body of literature, there is a significant confusion among researchers about the scale parameters involved in nonlocal elasticity theory and strain gradient theory. Investigations based of nonlocal elasticity theory have been reported a stiffness-softening mechanism in contrast with stiffness-hardening mechanism observed in conventional strain gradient theory. Based on a nonlocal-strain gradient elasticity, Lim, Zhang, and Reddy (2015) proved that wave characteristics of nanobeams could not be matched with those of experiments only using nonlocal elasticity or strain gradient theory. Most recently, few investigations have been carried out to examine combined effects of nonlocal and strain gradient elasticity in wave propagation, vibration and buckling analysis of nanostructures (Ebrahimi & Barati, 2016b, 2017b, c, Ebrahimi, Barati, Dabbagh, 2016, Ebrahimi, Barati, & Haghi, 2016, Li & Hu, 2015; Li, Hu, & Ling, 2015; Li, Li, & Hu, 2016).

The double-nanobeam system is constructed from two parallel nanoscale beams continuously connected via coupling medium. Such nanobeams have great applications in nano-electro-mechanical systems including nanoscale sensors and switches (Arani, Abdollahian, & Kolahchi, 2015). Therefore, understanding wave propagation and vibration behavior of such structures is of great importance in the research community (Arani, Kolahchi, & Mortazavi, 2014; Murmu & Adhikari, 2010; Murmu, McCarthy, & Adhikari, 2012; Şimşek, 2011). Moreover, porosities create inside the material during the construction of structures even at nanoscale (Zhang, Qian, Zhu, & Tang, 2014). Investigation of porosity effect in analysis of nanostructures is a novel topic which is reported by only a few researchers. Shaat and Abdelkefi (2016) examined buckling characteristics of nano-crystalline porous nanobeams via an analytical approach. Mechab, Mechab, Benaissa, Ameri, and Serier et al. (2016) and Mechab, Mechab, Benaissa, Serier, and Bouiadjra (2016) examined free vibrational behavior of FGM nanoscale plates with porosities according to a higher order refined plate model. They concluded that volume fraction of porosities inside the material significantly changes the frequencies.

In this study, a double-nanobeam system is modeled via a generalized bi-Helmholtz nonlocal-strain gradient theory to examine the wave characteristics at nanoscale. Three scale parameters called lower order, higher order nonlocal parameters as well as a strain gradient parameter are considered in the model to appropriately capture the small size effects. Graded material properties of nanobeams are porosity-dependent based on a modified rule of mixture. Governing equations of embedded double-nanobeam system derived from Hamilton's principle are analytically solved to obtain wave characteristics. A parametric study is performed to examine the influences of interlayer stiffness, nonlocal parameters, strain gradient parameters, porosities and material composition on wave characteristics of such double-nanobeam systems.

2. Theory and formulation

2.1. Porosity-dependent functionally graded materials

The volume fractions of ceramic and metal phases based on the P-FGM model are considered as (Wattanasakulpong & Ungbhakorn, 2014; Yahia, Atmane, Houari, & Tounsi, 2015):

$$V_c = \left(\frac{z}{h} + \frac{1}{2}\right)^p - \frac{\xi}{2}, V_m = 1 - \left(\frac{z}{h} + \frac{1}{2}\right)^p - \frac{\xi}{2} \tag{1}$$

in which p and ξ are power-law index and porosity volume fraction, respectively. Finally, the effective Young's modulus $E(z)$, density $\rho(z)$ and thermal expansion coefficient $\alpha(z)$of the nonlocal P-FGM beam can be expressed in the following form (Wattanasakulpong & Ungbhakorn, 2014; Yahia et al., 2015):

$$E(z) = E_m + (E_c - E_m)\left(\frac{z}{h} + \frac{1}{2}\right)^p - \frac{\xi}{2}(E_c + E_m) \tag{2a}$$

$$\rho(z) = \rho_m + (\rho_c - \rho_m)\left(\frac{z}{h} + \frac{1}{2}\right)^p - \frac{\xi}{2}(\rho_c + \rho_m) \tag{2b}$$

$$\alpha(z) = \alpha_m + (\alpha_c - \alpha_m)\left(\frac{z}{h} + \frac{1}{2}\right)^p - \frac{\xi}{2}(\alpha_c + \alpha_m) \tag{2c}$$

Based on the model defined in Eq. (2), upper and lower sides of nanobeams are pure ceramic and pure metal respectively and their material properties are listed in Table 1. Also, geometry of functionally graded double-nanobeam system is shown in Fig. 1.

2.2. Kinematic relations

The displacement field at any point of the nanobeam according to Euler–Bernoulli beam theory is defined by:

$$u_x(x,z,t) = u(x,t) - z\frac{\partial w(x,t)}{\partial x} \tag{3a}$$

$$u_z(x,z,t) = w(x,t) \tag{3b}$$