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A nonlocal strain gradient theory for wave propagation analysis in temperature-dependent inhomogeneous nanoplates

Farzad Ebrahimi*, Mohammad Reza Barati, Ali Dabbagh

Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran

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ABSTRACT

In this paper, wave propagation analysis of an inhomogeneous functionally graded (FG) nanoplate subjected to nonlinear thermal loading is investigated by the means of nonlocal strain gradient theory. The model introduces a nonlocal stress field parameter and a length scale parameter to capture the size effect. Shear deformation effects are taken into account by using a four-variable refined shear deformation plate theory. Nonlinear thermal loading relation is derived by solving a heat conduction problem through the thickness of the nanoplate. Material properties are assumed to be temperature-dependent and change gradually through the thickness via Mori–Tanaka model. The governing equations are developed employing Hamilton's principle. The results of present work are validated by comparing to those of previous works. The effects of various parameters such as nonlocal parameter, length scale parameter, gradient index and temperature distribution on the wave dispersion characteristics of size-dependent nanoplates have been studied.

1. Introduction

Functionally graded materials (FGMs) are known as the great materials in mechanical properties, thermal and corrosive resistance. For the first time a group of Japanese scientists in the mid-1980s, introduced FGMs as a novel generation of composites of microscopically heterogeneous materials and as thermal barrier materials in severe temperature environments. FGMs were recovered by controlling the volume fractions, microstructure, porosity, etc. of the material constituents during manufacturing, resulting in spatial gradient of macroscopic material properties. In the last decade, the trend of using beams and plates made of FGMs for engineering structures has significantly increased. Therefore, understanding the behavior of structures made of porous FGMs subjected to a variety of mechanical and thermal loadings is very important for their accurate design.

Nanoscale structures are of significance in the field of nano-mechanics, so it is crucial to account for small size influences in their mechanical analysis. The lack of a scale parameter in the classical continuum theory makes it impossible to describe the size effects. Hence, size dependent continuum theories such as nonlocal elasticity theory (Eringen, 1972 & 1983) and nonlocal strain gradient theory (Yang, Chong, Lam, & Tong, 2002) are developed to consider the small scale effects. The nonlocal elasticity theory is used to analyze the mechanical response of nanostructures by many authors (Ebrahimi & Barati, 2015; Fotouhi, Firouz-Abadi, & Haddadpour, 2013; Lei, Adhikari, & Friswell, 2013; Naderi & Saidi, 2014; Nejad & Hadi, 2016a;

* Corresponding author.
E-mail address: febrahimy@eng.ikiu.ac.ir, febrahimy@gmail.com (F. Ebrahimi).

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Reddy, 2007; Reddy & El-Borgi, 2014). Investigation of size effects on wave propagation behavior of nanoplates resting on elastic medium is performed by Wang, Li, & Kishimoto (2010a). Wang, Li, & Kishimoto (2010b) have also investigated the size effects on axial wave propagation of nanoplates employing nonlocal elasticity. Studied the thermal effects on ultrasonic wave propagation characteristics of nanoplates. Small size effect on the wave propagation of a piezoelectric nanoplate is studied by Zhang, Liu, Fang, & Nie (2014a) via nonlocal elasticity theory. Zhang, Liu, Fang, & Nie (2014b) investigated wave propagation behavior of nanoplates incorporating surface stress effects. Also, Zang, Fang, Zhang, Yang, & Li (2014) showed the size effects on the axial wave propagation of a piezoelectric nanoplate considering surface effects. Despite the fact that Eringen's theory is broadly applied to take into consideration of the small scale effects, it considers only the stiffness-softening influence. Various researchers (Fleck & Hutchinson, 1993; Lam, Yang, Chong, Wang, & Tong, 2003; Stolken & Evans, 1998) have indicated a stiffness enhancement that is not included in nonlocal elasticity. It is reported that the nonlocal elasticity theory is unable to predict the stiffness-hardening effects by introducing the length scale parameter. In the nonlocal strain gradient theory the stress field accounts for not only the nonlocal stress field but also the strain gradients stress field. Akgöz & Civalek (2013) have developed a new shear deformation beam theory by the means of strain gradient theory. The nonlinear vibration responses of nanobeams which are elastically bonded to piezoelectric nanobeams have been shown by applying the strain gradient theory by Arani, Abdollahian, & Kolahchi (2015). The size-dependent bending characteristics of an electro-elastic bilayer nanobeam is studied by Qi, Zhou, & Li (2016). It is clear that the conventional strain gradient theory is unable to consider the nonlocality of strain gradient stress field. Recently, Lim, Zhang, & Reddy (2015) proposed a nonlocal elasticity and strain gradient theory for the wave propagation analysis of size-dependent structures. Farajpour, Yazdi, Rastgoo, & Mohammadi (2016) has recently used the nonlocal strain gradient theory to study the buckling characteristics of nanoplates. Li, Hu, & Ling (2016) analyzed wave propagation in carbon nanotubes with surface effects based on nonlocal strain gradient theory.

Recently, a remarkable attention in research community is paid to static and dynamic analysis of nonlocal FG nanostructures. Rahmani & Pedram (2014) investigated size effect on vibration behavior of functionally graded nanobeams based on nonlocal Timoshenko beam theory. Stability analysis of size dependent functionally graded nanoplate are explored based on nonlocal elasticity and higher order plate theories and different boundary conditions by Daneshmehr & Rajabpoor (2014). Free vibration behaviors of FG nanoplates considering small scale effects are investigated by Daneshmehr, Rajabpoor, & Hadi (2015). Salehipour, Shahidi, & Nahvi (2015) employed the modified nonlocal elasticity theory for functionally graded materials while Shafiei, Kazemi, Safi, & Ghadiri (2016) investigated nonlinear vibration of axially functionally graded non-uniform nanobeams. Nejad & Hadi (2016b) employed Eringen's nonlocal elasticity theory for bending analysis of bi-directional functionally graded Euler–Bernoulli nano-beams. Thermo-elasto-dynamic analysis of axially functionally graded non-uniform nanobeams was studied by Kiani (2016) considering the surface energy effects. Thermal buckling and free vibration characteristics of FG nanobeams subjected to temperature distributions have been investigated by Ebrahimi & Salari (2015). Thermo-mechanical vibration response of FG nanobeams under linear and nonlinear thermal loadings has been investigated by Ebrahimi, Salari, & Hosseini (2015). Ebrahimi & Barati (2016a) studied the vibration behaviors of magneto-electro-thermo-elastic FG nanobeams based on a third order shear deformation beam theory. The buckling analysis of FG piezoelectric nanobeams rested on an elastic foundation is performed by Ebrahimi & Barati (2016b) in the framework of a higher-order beam theory.

Moreover, there are lots of theories which are employed in analysis of the static, vibration, buckling and wave propagation responses of plates. The simplest theory is called classical plate theory (CPT) which neglects the shear deformation effects. Since the application of FGMs increases, more exact plate theories are needed to estimate the response of FG plates, therefore, higher-order shear deformation theories (HSDTs) are suggested. Shear deformation effects are taken into account in HSDTs, so these theories do not need a shear correction factor. Recently, four-variable refined plate theories are developed and used to investigate the responses of FG plates. A refined higher-order plate theory for vibration analysis of FG plates is proposed by Thai & Choi (2012). Thai, Park, & Choi (2013) used a parabolic refined higher-order plate theory for vibration analysis of FG plates. Yahia, Atmane, Houari, & Tounsi (2015) investigated the effect of porosity on wave propagation responses of FG plates using refined higher-order shear deformation theories. Mechab, Mechab, Benaissa, Ameri, & Serier (2016) investigated vibration analysis of porous FG nanoplates using a four-variable refined plate theory. An electro-magneto wave propagation analysis is performed via a refined plate theory for a viscoelastic sandwich nanoplate regarding the small scale effect by Arani et al. (2015). Thermal buckling behavior of a FG nanoplate resting on an elastic foundation in different types of thermal environments is investigated with a new higher-order refined theory by Barati, Zenkour, & Shahverdi (2016).

It is obvious that vibration and buckling analysis of FG nanobeams and FG nanoplates are plenty, however, there are few articles that investigate the wave propagation of such structures. Zhang et al. (2015) investigated the surface and thermal effects on the flexural wave propagation of piezoelectric FG nanobeams via nonlocal elasticity theory. The flexural wave propagation analysis of small-scaled FG beams is presented by Li, Hu, & Ling (2015) applying a nonlocal strain gradient theory. Therefore, there isn't any research on wave propagation of a FG nanoplate subjected to thermal loading with temperature-dependent material properties via nonlocal strain gradient theory.

In this paper, nonlocal strain gradient theory which contains both nonlocal and length scale parameter for more accurate description of size effects is employed to examine the wave propagation behavior of size-dependent FG nanoplates in thermal environments. The material properties of nanoplate change gradually through the thickness via Mori–Tanaka scheme and are considered to be temperature-dependent. The governing equations of FG nanoplate modeled via a refined four-