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Dynamic response of biaxially loaded double-layer viscoelastic orthotropic nanoplate system under a moving nanoparticle

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ABSTRACT

In this paper, dynamic behavior of double layered nanoplate systems (DLNPS) with respect to a moving nanoparticle is investigated. Both layers of DLNPS are assumed to be orthotropic and each layer is bearing a biaxial load while internal damping effects are also taken into account. Furthermore, coupling between layers are modeled using Kelvin-Voigt viscoelastic theory and moving nanoparticles path are assumed to be linear and circular with constant velocities. Governing equations of motion are derived by using D'Alembert's principle, Kirchhoff-Love plate and Eringen's nonlocal theory. Galerkin's and Laplace transform methods is used to solve the governing equations and analytical solution is presented for linear moving nanoparticle while close-form solution is obtained for circular moving nanoparticle. In order to clarify the influence of different parameters such as small scale effect, stiffness and damping in coupling, biaxial compression and tension of layers, path of the moving mass, etc. on dynamic behavior of each layer, parametric study is presented. Accordingly, with the brand new discussions in moving atoms, molecules, nanocars, nanotrims, point loads on different nanosctructures using scanning tunneling microscopes (STM) and atomic force microscopes (AFM), this study could be a step forward in understanding such kind of behaviors.

1. Introduction

Nanoplates are one of the most important nanostructures used in many nano and micro systems such as oscillators (Qian, Hui, Liu, Kar, & Rinaldi, 2013), clocks (Tong, DiLabio, Clarkin, & Wolkow, 2004), sensors (Detsri, 2016; Ding, Zhang, Wei, & Su, 2015; Jing & Zhan, 2008; Reddy et al., 2011; Zhang et al., 2011), atomic force microscopes (Jeong et al., 2016; Tang & Lai, 2014) and NEMS/MEMS (Hui, Gomez-Diaz, Qian, Alu, & Rinaldi, 2016; Nan, Hui, Rinaldi, & Sun, 2013) devices. Due to the small scale effects, these nanostructures show significant behavior under different mechanical, chemical and electronic conditions which it couldn't be described using classical theories. However, to be able to model these behaviors, different theories have been presented such as strain gradient theory (Fleck, Muller, Ashby, & Hutchinson, 1994; Lam, Yang, Chong, Wang, & Tong, 2003), modified couple stress theory (Bergman, 1968; Mindlin & Tiersten, 1962; Toupin, 1962), and nonlocal elasticity theory (Eringen, 1983; Eringen, 2002; Kröner, 1967) in which the Eringen's nonlocal elasticity theory achieved most attention between researchers in order to model and predict the behavior of nanoscructures. Unlike classical theories in continuum mechanics, nonlocal elastic theories consider the small scale effects by assuming that stress at a point

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is a function of strains at all points in the continuum model. Lots of studies have been done in order to comprehend the mechanical behavior of nanobeams, nanotubes and nanoplates in both static conditions such as bending (Fernández-Sáez, Zaera, Loya, & Reddy, 2016; Li & Hu, 2016; Nejad & Hadi, 2016; Reddy, 2007, Thai, 2011; Tuna & Kirca, 2016), buckling (Dai, Wang, Abdelkefi, & Ni, 2015; Li & Hu, 2015; Nejad & Rastgoo, 2016a, Taati, 2016) and dynamic (Ebrahimi & Barati, 2016; Ebrahimi, Barati, & Dabbagh, 2016; Lei, Adhikari, & Friswell, 2013; Li et al., 2016; Nejad & Rastgoo, 2016b, Rahmani & Pedram, 2014) manners. According to the vast application of nanostructures as sensors (Huang & Choi, 2007; Motta, 2015; Motta, 2012; Stewart et al., 2008; Wei, Pan, & Huang, 2011; Zhao et al., 2006; Zribi & Fortin, 2008) in different kind of systems, it is important to understand the behavior of nanoplates under different actuating forces like moving loads, sinusoidal loads, static forces, etc. To reach this goal, scientist have done some researches in recent years using both experimental and theoretical studies. Although the experimental studies give more reliable results, providing experimental conditions with less noise for every type of force on the surfaces is too expensive and almost impossible which caused more concentration on theoretical studies specially by employing Eringen's nonlocal elasticity theory. Also, with the investigation of nanocars (Shirai, Osgood, Zhao, Kelly, & Tour, 2005) in Rice University in 2005 the movement of them on different surfaces became an important issue for scientists. Afterward, Many researches have been done in order to optimize (García-Lopez et al., 2016; Godoy, Vives, & Tour, 2010; Sasaki & Tour, 2007; Sasaki, Guerrero, & Tour, 2008; Vives & Tour, 2009a) and motorize (Chiang et al., 2012; García-Lopez et al., 2015; Morin, Shirai, & Tour, 2006) them, making new designs by presenting nanotrucks and nanotrimers (Akimov, Nemukhin, moskovsky, Kolomeisky, & Tour, 2008; Morin, Sasaki, Shiari, Guerrero, & Tour, 2007; Vives & Tour, 2009b). These studies leaded to a nanorace (Rutkin, 2016) between nanocars from different universities and companies in 2016–2017. On the other hand, scanning tunneling microscopes (STM) and atomic force microscopes (AFM) is being used in order to study the movement of atoms (Celotta et al., 2014; Custance, Perez, & Morita, 2009; Gross et al., 2005; Hla, 2005), molecules (Moll et al., 2014; Nickel et al., 2012; Weymouth, Hofmann, & Giessibl, 2014) and cells (Beaussart et al., 2014; Cartagena & Raman, 2014) on different nanostructures in order to understand the effects of atomic structures, how atoms move and interact and how they guide the flow of electrical current and modelling the nanostructure as smallest magnetic memory. This shows the importance of understanding the reaction of nanostructures under such kind of dynamic conditions. To this end, Kiani (2011a) investigated the vibration of elastic thin single layered nanoplate traversed by a moving nanoparticle involving Coulomb friction. The Eigen function technique and the Laplace transform method were employed to solve the governing equations of single layered nanoplate. Nanoparticles movement was assumed to be with constant speed on an arbitrary straight line path. Eringens nonlocal elasticity theory was used to model the small scale effects and a parametric study for nonlocal effects were presented. Kiani (2011b, c) also theoretically modeled the formulation of dynamic response of single layered thin plates under a constant speed moving nanoparticle by adding biaxial forces to the single layered thin nanoplate. Kiani (2013) also studied the vibration of Biaxially Tensioned-embedded Nanoplates for Nanoparticle Delivery. Ghorbanpour Arani, Kolahchi, and Gharbi Afshar (2015) studied dynamic qualitative analysis and vibration response of an embedded poly-vinylidene fluoride (PVDF) nanoplate under a moving nanoparticle on an arbitrary elliptical path. The elastic medium and small scale effect were modeled after Pasternak and Eringens nonlocal elastic theory. Based on energy method, Hamilton's principle and Galerkin's method, equation of motions and the closed-form solutions for the frequency and dynamic deflection of the nanoplate were calculated and the coupled motion equations were derived. Parametric study was conducted to elucidate the influences of the nonlocal and other parameters on the vibration smart control of the PVDF nanoplate. Darvish Ganji, Ghorbanzadeh Ahangari, and Emami (2014) investigated the nanocars motion on a graphene/graphyne substrate using first-principles vdW-DF calculation. Two different types of nanocar wheel movement (slipping and slithering) were considered. First-principles molecular dynamics simulation was also used to consider the type of nanocar movement on the substrate. It was shown that the nanocar would require at least −71.39 and −18.33 kJ mol-1 to activate its movement on the graphene and graphyne surfaces. Nejat Pishkenari, Nemati, Meghdari, and Sohrabpour (2015) studied the motion of buckminsterfullerene (C60) on a gold surface by analyzing its potential energy and using classical molecular dynamics method. It was presented that the rotational motion of the C60 molecule on the gold substrate, was easier than its sliding (translational) motion. Also, the regime of motion of fullerene depended on temperature. Ghorbanzadeh Ahangari, Darvish Ganji, and Jalali (2016) studied the interaction between fullerene-wheeled nanocar and gold substrate. Nami and Janghorban (2015) studied the dynamic analysis of rectangular nanoplates subjected to moving load. Second order plate theory was used to model derive the equation of motions. The moving load was assumed to be a concentrated force with a constant speed in only x direction. With the use of state-space method the results were achieved and the effect of nonlocality was discussed.

With the knowledge of the authors, there is no studies done in order to investigate the reaction of double-layered or multi-layered nanoplates under a moving load, mass or nanovehicles. In this study, dynamic behavior of bi-axially loaded double layered viscoelastic orthotropic nanoplates is presented under a moving nanoparticle and accordingly, the schematic of the system is presented in Fig. 1. Moreover, nanoplates are modeled using Kirchhoff-Love plate theory and each layer are assumed to be under a different biaxial load. Coupling between layers is modeled after Kelvin-Voigt viscoelastic medium theory which concludes both stiffness and damping parameters and Eringen's nonlocal theory is used to model the small scale effects. The moving mass is assumed to be concentrated and the study is done for two different paths, first it is assumed that the nanoparticle passes through a straight line with a constant angle with x direction as shown in Fig. 2a and the second path is assumed to be a circular path with an arbitrary center and radius as shown in Fig. 2b. Analytical solution is presented using Eigen function technique and Laplace transform method for linear moving mass and close-form