International Journal of Engineering Science 103 (2016) 97–113

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Transient behavior of an orthotropic graphene sheet resting on orthotropic visco-Pasternak foundation

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A R T I C L E   I N F O

Article history:
Received 18 September 2015
Revised 3 January 2016
Accepted 7 February 2016
Available online 20 April 2016

Keywords:
Transient analysis
Viscoelastic orthotropic graphene sheet
Fourier series-Laplace transform
Nonlocal elasticity theory
Orthotropic visco-Pasternak foundation

A B S T R A C T

This paper deals with transient analysis of simply-supported orthotropic single-layered graphene sheet (SLGS) resting on orthotropic visco-Pasternak foundation subjected to dynamic loads. The size effect is taken into account using Eringen's nonlocal theory due to its simplicity and accuracy. In order to present a realistic model, the material properties of graphene sheet are supposed viscoelastic using Kelvin–Voigt model. Based on the first order shear deformation theory (FSDT), equations of motion are derived using Hamilton's principle which are then solved analytically by means of Fourier series-Laplace transform method. The present results are found to be in good agreement with those available in the literature. Some numerical results are presented to indicate the influences of size effect, elastic foundation type, structural damping, orthotropy directions and damping coefficient of the foundation, modulus ratio, length to thickness ratio and aspect ratio on the dynamic behavior of rectangular SLGS. Results depict that the structural and foundation damping coefficients are effective parameters on the transient response, particularly for large damping coefficients, where response of SLGS is damped rapidly.

1. Introduction

Graphene, a single atomic layer of graphite arranged in a two dimensional honeycomb structure, is one of the most famous and beloved types of carbon structures among researchers because of its superior electrical, thermal, chemical, optical and mechanical properties. For this reason it is vastly used in nano-electro-mechanical systems (NEMS) such as sensors (Murmu & Adhikari, 2013; Sakhaee-Pour, Ahmadian, & Vafai, 2008), nano-sheet resonators (Eichler et al., 2011), nanoactuators (Ji et al., 2012), conductive electrodes for solar cells (Wang, Zhi, & Müllen, 2008) and so on. Hence, investigating the behavior of nano-mechanical systems made of graphene helps in better designing.

Generally, three major procedures have been developed to analyze the mechanical properties of nanostructures known as molecular dynamics (MD) simulations, experimental study and continuum mechanics approach. The first two methods are very cumbersome and computationally prohibitive for nanostructure systems with large number of atoms. Thus, because of these limitations, continuum mechanic approaches have been known as powerful and effective methods to study mechanical characteristics of nanostructures. Since the classical continuum mechanics have no ability in capturing the small scale effects, it cannot be regarded as a reliable theory to predict the mechanical behavior of nanomaterials. So far, several non-classical continuum theories have been formulated to incorporate the small-scale size effects in micro/nano structures, such

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http://dx.doi.org/10.1016/j.ijengsci.2016.02.006

as nonlocal elasticity theory (Eringen, 1972; Lei, Adhikari, & Friswell, 2013; Najar, El-Borgi, Reddy, & Mrabet, 2015; Reddy, 2007; Reddy & El-Borgi, 2014), strain gradient theory (Ghayesh, Amabili, & Farokhi, 2013; Kong, Zhou, Nie, & Wang, 2009; Lam, Yang, Chong, Wang, & Tong, 2003; Wang, 2010) and couple stress theory (Akgöz & Civalek, 2012; Dai, Wang, & Wang, 2015; Ghayesh & Farokhi, 2015; Ghorbanpour Arani, Abdollahian, & Jalaei, 2015; Mohammad-Abadi & Daneshmehr, 2014). Among these size dependent theories, the nonlocal elasticity theory initiated by Eringen (1983, 2002) has been widely used in the study of structures at small scale. In this theory, the nonlocal stress tensor at a reference point in a body depends not only on the strain tensor at that point, but also on the strain tensor at all other points in the body. The literature shows that nonlocal theory is being increasingly utilized for reliable and quick analysis of nanostructures in recent years. In this regard, a number of research works have been performed based on this theory in order to study on the bending (Aghababaei & Reddy, 2009; Scarpa, Adhikari, Gil, & Remillat, 2010; Wang & Li, 2012), buckling (Ansari & Rouhi, 2012; Daneshmehr, Rajabpoor, & Pourdavood, 2014; Karamooz Ravari, Talebi, & Shahidi, 2014; Narendar, 2011; Samaei, Abbasion & Mirsayar, 2011; Sarrami-Foroushani & Azhari, 2014) and vibration (Aghababaei & Reddy, 2009; Assadi, Farshi, & Alinia-ZiaZi, 2010; Daneshmehr, Rajabpoor, & Hadi, 2015; Jomehzadeh & Saidi, 2011; Liew, He, & Kitipornchai, 2006; Malekzadeh & Shojaee, 2013; Pradhan & Kumar, 2011; Pradhan & Phadikar, 2009; Sarrami-Foroushani & Azhari, 2014) of graphene sheets. Reddy, Rajendran, and Liew (2006) computed elastic constants of the graphene sheet based on the Brenner's potential and the Cauchy-Born rule. It has been shown that due to the variation in coordination number, the equilibrium bond length of carbon-carbon is not uniform everywhere in the graphene. They found that graphene behaves like an orthotropic material. Mohammadi, Farajpour, Goodarzi, and Shehni nezhad pour (2014) presented nonlocal theory to study the free vibration of orthotropic single-layered graphene sheet (SLGS) resting on a Pasternak foundation under shear in-plane load based on classical plate theory (CLPT) and used the combined Galerkin-differential quadrature method to solve the obtained equations. They concluded that increasing nonlocal parameter reduces the non-dimensional frequency of the SLGS. Also, the small scale effects are more significant for the nanoplate with shear in-plane load compared to nanoplate without shear in-plane load. Arash, Wang, and Liew (2012) investigated an inclusive research on wave propagations in SLGS by the nonlocal finite element plate model and MD simulations. They found that nonlocal finite element (FE) model is essential in analysis of graphene sheets (GSs), especially at wavelengths less than 1 nm. The elastic buckling and vibration analyses of isotropic and orthotropic GSs under biaxial compression and pure shear loading based on Eringen's nonlocal theory using the spline finite strip method were reported by Analooei, Azhari, and Heidarpour (2013). They revealed that the buckling behavior of nanoplate subjected to shear loading is more sensitive to the small scale effects than it under biaxial loading. Also, their work indicated that by increasing the dimensions of nanoplate, size effect reduces. Ansari, Rajabiehfard, and Arash (2010) reported a finite element method (FEM) based on the nonlocal theory to investigate the small scale effect on the vibration analysis of multi-layered graphene sheets (MLGSs) with various boundary conditions embedded in an elastic medium. They found that by increasing nonlocal parameter, the size dependency increase in all of boundary conditions. In addition, their results indicated that the natural frequencies more sensitive to the nonlocal parameter in higher mode number. Rayleigh-Ritz solution for nonlocal vibration behavior of isotropic rectangular nanoplates with different boundary conditions on the basis of CLPT was presented by Chakraverty and Behera (2014). They observed that when the aspect ratio increases, the frequency parameter increases. Their work also showed that frequency parameters are highest in nanoplate with fully clamped boundary condition. Nonlinear nonlocal vibration response of the coupled system of double-layered annular graphene sheets (CS-DLAGSs) embedded in a visco-Pasternak medium was investigated numerically using differential quadrature method (DQM) by Ghorbanpour Arani, Maboudi, and Kolahchi (2014). They revealed that the frequency reduction percent (FRP) of in phase-in phase-in phase (III) and out phase-out phase-out phase (OOO) vibration state are maximum and minimum, respectively. In addition, their results indicated that the FRP of Visco-Winkler and Pasternak mediums are maximum and minimum, respectively. Employing nonlocal theory and von-Kármán model, Naderi and Saidi (2014) researched postbuckling behavior of orthotropic GSs in nonlinear polymer medium under both uniaxial and biaxial in-plane loadings. They solved equilibrium equations via the Galerkin method for GSs with various boundary conditions based on the CLPT. They observed that the small scale effects are obvious especially on Postbuckling behavior of nanoplate having stiffer boundary conditions. Also, their work showed that when the external loads increases, the nonlinearity effect increases.

All the above mentioned researches have been conducted on the nonlocal continuum models for buckling and free vibration of graphene sheets, however a little attention has been devoted to the bending problem of graphene sheets based on the nonlocal elasticity theory. In this regard, Kanaipour (2014) studied static bending analysis of nanoplate embedded on elastic foundation. The governing equations for the nonlocal Mindlin and Kirchhoff plate models were derived and then were solved numerically using DQM. He revealed that when the nanoplate becomes thicker, nonlocal Mindlin plate model is more appropriate. Also, he observed that by increasing the elastic stiffness, the displacement ratio increases. The nonlinear bending response of rectangular orthotropic SLGS resting on Pasternak foundation, subjected to uniform load presented by Golmakani and Rezatalab (2014) based on nonlocal first order shear deformation theory (FSDT). The governing equations were obtained with assumption of von-Kármán relationship and then were solved using DQM for various types of boundary conditions. Their results showed that when the elastic foundation exists, the linear to nonlinear deflection ratio decreases.

In the field of transient analysis of nanoplate, Liu and Chen (2014) analyzed dynamic response of the finite periodic SLGSs with different boundary conditions using the wave method on the basis of the nonlocal Mindlin plate theory. They found that dynamic displacement responses of finite GSs can be reduced much by periodic arrangement design. Also, their work indicated that the transverse shear strain responses for the periodic nanoplate in the band gap frequency domain are much smaller than those of uniform ones. Most recently, Ghorbanpour Arani and Jalaei (2015) investigated static bending