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Analytical solution for static and dynamic analysis of magnetically affected viscoelastic orthotropic double-layered graphene sheets resting on viscoelastic foundation

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A B S T R A C T

By considering the small scale effect based on the nonlocal Eringen's theory, the static and dynamic analysis of viscoelastic orthotropic double-layered graphene sheets subjected to longitudinal magnetic field and mechanical load is investigated analytically. For this objective, first order shear deformation theory (FSDT) is proposed. The surrounding medium is simulated by visco-Pasternak foundation model in which damping, normal and transverse shear loads are taken into account. The governing equations of motion are obtained via energy method and Hamilton's principle which are then solved analytically by means of Navier's approach and Laplace inversion technique in the space and time domains, respectively. Through various parametric studies, the influences of the nonlocal parameter, structural damping, van der Waals (vdW) interaction, stiffness and damping coefficient of the foundation, magnetic parameter, aspect ratio and length to thickness ratio on the static and dynamic response of the nanoplates are examined. The results depict that when the vdW interaction is considered to be zero, the upper layer deflection reaches a maximum point whereas the lower layer deflection becomes zero. In addition, it is observed that with growing the vdW interaction, the effect of magnetic field on the deflection of the lower layer increases while this effect reduces for the upper layer deflection.

1. Introduction

In recent years, a significant degree of attention has been paid to research surrounding two main allotropes of carbon, namely graphene sheets and carbon nanotubes (CNTs) due to their exceptional properties as components in micro/nano electro-mechanical systems (MEMS/NEMS). Graphene is a two-dimensional atomic crystal which is formed in hexagonal shape by covalent bonds between carbon atoms. Owing to the remarkable properties such as high strength, low weight and extraordinary electrical and thermal conductivities as well as sensitive to magnetic field, graphene sheets can be vastly used in various fields of modern nanotechnology such as nanoactuators [1], mass and pressure sensors [2, 3], solar cells [4], composite materials [5], biomedical [6], magnetic and electric field sensors [7] and etc.

Similar to CNTs, graphene sheets can be utilized as an excellent reinforcement in composites to improve the mechanical, thermal and electrical properties of them. In recent years, the mechanical response of these materials has been a new subject of investigation among the researchers which has a great potential for future engineering applications. Complex-nanoplate-systems based on two or more graphene sheets embedded into polymer matrices are a notable class of nanocomposites which significantly enhance the properties of host materials. These graphene-based composites have a huge potential for many applications, such as conductors, fuel cells, lithium-ion batteries, electronics, sensors and supercapacitors. Hence, it is essential to accurately predict mechanical behavior of these materials for developing and fabricating future composites. Besides experimental methods, there are two main theoretical modeling approaches that have been developed to analyze the mechanical behavior of nanostructures such as atomistic simulations and continuum mechanics. The atomistic-based method such as molecular dynamics (MD) simulation, tight-binding molecular dynamics (TBMD) and density functional theory (DFT) can be utilized for systems with small number of molecules and atoms. Since classical continuum mechanics are not able to consider small scale effects that are present on the nano-scale structures, several nonclassical continuum theories such as strain gradient theory [8–10], couple stress theory [11–14] and nonlocal

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elasticity theory [15–19] have been developed to characterize the size effects in micro/nano structures.

Among these theories, the nonlocal elasticity theory introduced by Eringen [15] has been widely applied because of convenience in formulations and close agreement with lattice dynamics and MD simulation results.

Double-layered graphene sheets (DLGSs) have potential application for the manufacturing of new nanoscale devices which can be used in polymer composites as embedded structures to enhance their strength. Therefore, bonded complex systems are vital from both theoretical and practical point of view. To this end, many studies have been recently carried out to investigate mechanical behavior of complex systems. In this regard, Wang et al. [20] performed flexural wave propagation analysis in elastically connected double-nanoplate-system (DNPS) based on the nonlocal classical plate theory (CLPT). Ansari et al. [21] studied the vibrational response of multi-layered graphene sheets (MLGSs) with various boundary conditions. The equations of motion were derived based on the nonlocal Reissner-Mindlin elasticity theory and then solved numerically by the generalized differential quadrature method (GDQM). Ghorbanpour Arani et al. [22] investigated vibration response of the coupled system of double-layered graphene sheets (CS-DLGSs) with different boundary conditions embedded in a visco-Pasternak foundation using DQM on the basis of the nonlocal elasticity orthotropic plate theory. Pouresmaeeli et al. [23] presented an analytical approach for nonlocal vibration of double-orthotropic nanoplates with all edges simply-supported embedded in an elastic medium. Murmu et al. [24] analyzed the buckling of DNPS subjected to biaxial compression employing an analytical method based on nonlocal elasticity theory that the two nanoplates of DNPS are bonded by an elastic medium. Xu et al. [25] investigated the nonlinear bending of a bilayer graphene sheets (BLGSs) subjected to a transverse uniform load in thermal environments including the van der Waals (vdW) interactions. Ghorbanpour Arani et al. [26] carried out nonlinear nonlocal CLPT for vibration analysis of the coupled system of double-layered angular graphene sheets (CS-DLAGSs) embedded in a visco-Pasternak medium using DQM. Anjomshoa et al. [27] developed a finite element approach for nonlocal buckling of orthotropic MLGSs embedded in the polymer matrix. They simulated the vdW interactions between the graphene layers and the graphene-polymer as a set of linear springs using the Lennard-Jones potential model. Karličić et al. [28] carried out the free transverse vibration analysis of nonlocal viscoelastic orthotropic multi-nanoplate system (MNPS) embedded in a viscoelastic medium based on the Kirchhoff plate theory. Radić et al. [29] utilized the CLPT incorporating the nonlocal elasticity theory to describe the buckling behavior of double-orthotropic nanoplate system subjected to biaxial compression using Navier method. They assumed that two nanoplates are bonded by Winkler elastic medium and surrounded by Pasternak elastic foundation. Karličić et al. [30] offered the exact closed-form solution for the vibration and biaxial buckling of a multi-nanoplate system (MNPS) embedded in the Winkler elastic medium based on the nonlocal CLPT via Navier's and trigonometric method. Sarrami-Foroushani and Azhari [31] employed semi-analytical finite strip method (FSM) to analyze the vibration and buckling of single-layered graphene sheet (SLGS) and MLGSs with various boundary conditions. Karličić et al. [32] performed a detailed analysis of the free longitudinal vibration of a viscoelastic double-nanorod system via analytical method. Hosseini Hashemi et al. [33] analyzed vibration of coupled double viscoelastic graphene sheets (CDVGS) based on the nonlocal CLPT using exact solution. The two SLGSs are simply supported and coupled by a visco-Pasternak medium. Sobhy [34] developed the nonlocal two-variable plate theory to illustrate the hygrothermal vibration behavior of double-layered orthotropic nanoplates embedded in an elastic medium. Recently, Dastjerdi and Jabbarzadeh [35] investigated the nonlinear static bending of bilayer orthotropic graphene sheets resting on Pasternak elastic foundation subjected to uniform transverse loads based on the first order shear deformation theory (FSDT). In this study, the governing motion equations were solved numerically via DQM. On the basis of the nonlocal FSDT, Ghorbanpour Arani and Jalaei [36] analyzed size-dependent transient behavior of viscoelastic orthotropic SLGS embedded in orthotropic visco-Pasternak medium subjected to uniform and sinusoidal dynamic loads. Zhang et al. [37] investigated the vibration response of viscoelastic double-walled carbon nanotubes (DWCNTs) embedded in viscoelastic medium based on nonlocal Euler-Bernoulli beam theory. Most recently, Zhou et al. [38] accomplished the free vibration of the rectangular double-layered orthotropic nanoplate system with Levy-type boundary conditions based on the nonlocal Kirchhoff plate theory using a rigorous analytical symplectic approach.

It is observed that external magnetic field can vary the stability of nanostructures without the necessity of changing the material and geometrical parameters of them. So in recent years, researchers have tried to improve structure performance by applying magnetic field. Murmu et al. [39] presented an analytical approach to study the transverse vibration of DWCNTs under the influence of longitudinal magnetic field via nonlocal Euler-Bernoulli beam theory and considering the Lorentz magnetic force obtained from Maxwell's relation. In Ref. [40] the same author investigated the influence of an in-plane magnetic field on the transverse vibration of a magnetically sensitive SLGS embedded in an elastic medium employing nonlocal Kirchhoff plate theory. Karličić et al. [41] analyzed the free transverse vibration of multiple viscoelastic CNTs embedded in viscoelastic medium under longitudinal magnetic field. Kiani [42] scrutinized the free transverse vibration of elastically supported DWCNTs embedded in an elastic matrix subjected to a longitudinally varying magnetic field based on the nonlocal Rayleigh, Timoshenko, and higher-order beam theories. In another work, Kiani [43] scrutinized the free vibration of conducting a nanoplate exposed to a unidirectional in-plane magnetic field based on the Kirchhoff, Mindlin plate, and Reddy plate theories in the context of the nonlocal theory. Zhang et al. [44] adopted the nonlocal elasticity theory combined with the CLPT to describe the vibration behavior of BLGSs affected by an in-plane magnetic field using the kp-Ritz method. Ghorbanpour Arani and Jalaei [45] investigated the influence of a longitudinal magnetic field on the dynamic response of viscoelastic orthotropic SLGS resting on viscoelastic foundation based on the sinusoidal shear deformation theory (SSDT). Zhang et al. [46] adopted the nonlocal elasticity theory combined with the CLPT to describe the vibration behavior of quadrilateral SLGS affected by an in-plane magnetic field using the kp-Ritz method.

Nevertheless, the review of the literature confirms that no research has been carried out to study on the static bending and dynamic response of an embedded viscoelastic orthotropic DLGSs subjected to longitudinal magnetic field and mechanical load based on FSDT via analytical method so far. Since complex nanoplate systems including DLGSs affected by magnetic field enable the practical application as nanoresonators or nanocomposites, analyzing the static and dynamic response of these nanostructures becomes more prominent in designing NEMS devices. In order to present a realistic model, the material properties of each SLGS are assumed to be viscoelastic using Kelvin–Voigt model. The surrounding elastic medium is considered as a visco-Pasternak foundation including spring, shearing and damping constants. The DLGSs are composed of two simply supported orthotropic graphene sheets which are assumed to be bonded by an internal elastic medium. Employing nonlocal elasticity theory of Eringen and considering the Lorentz magnetic force obtained from Maxwell's relation, nonlocal governing equations of size-dependent viscoelastic graphene sheets under magnetic field are obtained based on Hamilton's principle and then solved analytically using the Navier's and Laplace inverse methods in the space and time domains, respectively. To confirm the validity of present research, the results are compared with those reported in the literature. Afterwards, the influences of the nonlocal parameter, magnetic field, structural and foundation damping coefficients, elastic foundation parameter, vdW interactions between the layers, length to thickness and aspect ratio on the static bending and dynamic response of viscoelastic DLGSs are examined.