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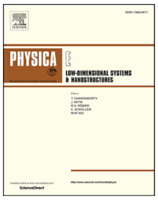

Hygrothermal wave propagation in viscoelastic graphene under in-plane magnetic field based on nonlocal strain gradient theory

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ABSTRACT

A size-dependent model is developed for the hygrothermal wave propagation analysis of an embedded viscoelastic single layer graphene sheet (SLGS) under the influence of in-plane magnetic field. The bi-Helmholtz nonlocal strain gradient theory involving three small scale parameters is introduced to account for the size-dependent effects. The size-dependent model is deduced based on Hamilton's principle. The closed-form solution of eigen-frequency relation between wave number and phase velocity is achieved. By studying the size-dependent effects on the flexural wave of SLGS, the dispersion relation predicted by the developed size-dependent model can show a good match with experimental data. The influence of in-plane magnetic field, temperature and moisture of environs, structural damping, damped substrate, lower and higher order nonlocal parameters and the material characteristic parameter on the phase velocity of SLGS is explored.

1. Introduction

Over the last few years, the trend of using nanoscale structures for engineering construction has significantly expanded. Hence, understanding the behavior of these structures subjected to a variety of mechanical, physical and environmental loadings is requisite for their accurate design. In response to this need, many size-dependent continuum theories have been introduced in order to overcome the lack of the scale-free classical continuum theory in nanoengineering applications for describing the size effects.

The strain-driven nonlocal elasticity theory [1,2] was presented to incorporate the effect of long-range interatomic forces. Mathematically, the elastic behavior of nanoscale structures with this theory includes a linear differential operator between the stress in a point of the domain with the strains in all other points of the domain. Therefore, the simplicity in comparison with the old one without considering size effect was enough to extremely used by scholars to analyze various nanoscale structures such like nanowire [3], nanoshell [4], nanotube [5–9], nanobeam [10,11] and nanoplate [12–17]. Furthermore, a review paper [18] gave an introduction of the development of the nonlocal continuum theory in modeling of graphene sheets (GSs) and carbon nanotubes. Despite this fact that leading-edge studies of the nonlocal continuum theories began in the sixties, in last years, there has been an increased interest in this subject (see, e.g. [19],) with exact solutions, which have been verified by using molecular dynamic (MD) simulation and experiments data (see, e.g. [20,21]). Recently, in the continuous development of the size-dependent continuum theories, the applicability of bi-Helmholtz nonlocal continuum model [22] including two distinct nonlocal parameters under the name of low-order nonlocal parameter and high-order nonlocal parameter was examined [23]. By focusing on MD simulation results, they believed that the bi-Helmholtz nonlocal model is more suitable than one parameter nonlocal model to deal with softening problems in nanoscale structures, such as carbon nanotubes (CNTs). What is more, by using the bi-Helmholtz nonlocal model, Shaat and Abdelkefi [24] verified the wave dispersion behavior of nanobeams with those of experimental data, and showed its accuracy can be better than that of nonlocal continuum model with one nonlocal parameter. It has been recently shown by some researchers [9,25] that inconsistency (or even paradox) is appeared in the physical behaviors of one-dimension problems based on strain-driven nonlocal constitutive relation. The innovative stress-driven model for nonlocal elasticity, first proposed in Romano and Barretta [26], consists in swapping input and output fields in the integral convolution. This new approach can be alternatively chosen to eliminate the paradoxical results due to non-existence of

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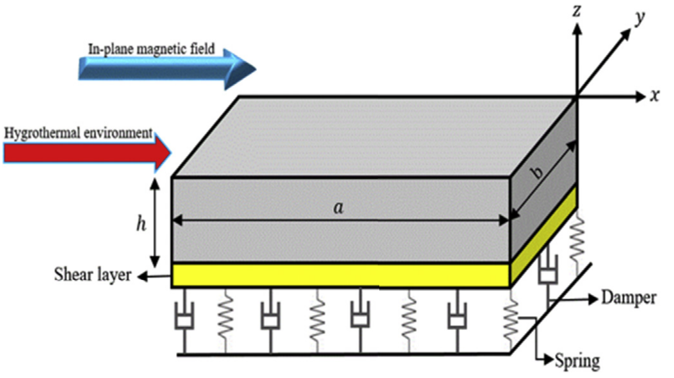

Fig. 1. A viscoelastic single layer graphene sheet coupled by a visco-Pasternak foundation in the hygrothermal environment under an in-plane magnetic field.

solution of strain-driven nonlocal elasticity problems on bounded domains, as successfully exploited in Refs. [27–29].

Furthermore, the capacity of strain-driven nonlocal continuum models [1] may exist some limited problems [30,31]. For example, by applying the nonlocal elasticity theory, the stiffness-enhancement effect, which has been observed via the strain gradient elasticity theory [32] as well as experimental investigations [33], cannot be predicted well. In contrast to the nonlocal continuum models, the strain gradient elasticity theory with one gradient parameter [34] assumes that the strain in a point is a function of all strains in all other points of the domain by using a strain gradient. On the basis of this theory, the size-dependent effect is also considered with a small length parameter (known as material characteristic parameter). Overall, according to modified Hooke's law of nonlocal strain gradient theory [31,35,36], the nonlocal parameter is used on the Laplacian of stresses on the left side of the constitutive equation, but the material characteristic parameter is considered on the right side of the equation on the Laplacian of strains. Actually, it is shown by Zhu and Li [37] that the nonlocal strain gradient model can be viewed as a combination of the constitutive equations of the strain-driven and stress-driven nonlocal theories. This nonlocal strain gradient model can estimate the softening-stiffness or stiffness-enhancement effect, depending on the ratio of nonlocal parameter to material characteristic parameter [38–43]. Besides that, the matching between the results of the nonlocal strain gradient models and experimental data (or MD simulation results) has been shown to be reasonably good [44], especially in wave dispersion of rod-type, beam-type and plate-type nanostructures [31,36,37,44–47]. Hence, in the last three years, many authors have been tried to use this model to analyze the size-dependent wave propagation behaviors of elastic nanobeams and nanotubes [31,36,48] and nanoplates [45,46,49,50] under the influence of magnetic field [51–53], thermal environment [54], elastic substrate [54], and viscoelastic substrate [50]. The wave dispersion analyses of porous double-nanobeam systems on the basis of bi-Helmholtz nonlocal strain gradient elasticity theory in the absence [55] and presence [56] of thermal environments are successfully presented.

It is known that, in practical applications, nanoscale structures (e.g., GSs) often work in environmental conditions [57]. Therefore, it is very necessary to propose diverse models which can be used to predict the mechanical and properties behaviors of GSs at different environmental conditions. The environmental conditions can include wet-dry, freeze--thaw, sea-water and moisture impression. Among them, temperature variation and moisture absorption are most attractive conditions for the mechanical analysis of GSs. This is because, for environment-dependent models of these structures, it is accepted that changing temperature and humidity causes evil effects in material strength and stiffness [58,59]. With returning to ready literature, many MD simulations and continuum mechanics-based studies have been tried to propose a model with considering the influence of environmental conditions. For example, elastic properties of zigzag and armchair GSs with various values of aspect ratio under temperature varying from 300 K to 700 K have been measured by using MD simulation [59]. Based on their results, the material properties of single layer graphene sheets (SLGSs) are size-dependent and temperature-dependent. Next, they determined the frequency [60] and static deflections [61] of GSs under temperature effect by continuum mechanics-based method as well as MD simulation. They showed that the mechanical behaviors of SLGSs in the thermal environment can predict well by using nonlocal elasticity theory with choosing an appropriate nonlocal parameter. Due to the importance of other environmental conditions on the behaviors of SLGSs, Han et al. [62] introduced the moisture-responsive of SLGSs using the self-controlled photoreduction experimentally. In this research, it was shown that the SLGS exhibits moisture-responsive properties due to selective adsorption of water molecules. Besides, the effects of temperature-moisture environment on the nonlocal vibration [63–65], bending [66,67], buckling [68,69], wave propagation [54,70,71] of SLGSs have been carried out analytically. It was found that the influence of temperature and moisture on nonlocal mechanical behaviors of SLGS is more important than that on local behaviors. Also, Shahsavari et al. [13] analytically studied the influence of hygrothermal environment on the dynamic response of viscoelastic nanoplates under moving load, and showed that the hygrothermal effect is significant, especially for high values of the nonlocal parameter.

With respond to the open literature, due to the best of our knowledge, up to now, analytical study has not been tried to propose a bi-Helmholtz nonlocal strain gradient model for wave dispersion analysis of SLGSs. In order to overcome this limitation, the present article will study the influences of heat and moisture conduction as well as an in-plane magnetic field on the wave behavior of viscoelastic orthotropic nanoplate resting on a visco-Pasternak foundation. The bi-Helmholtz nonlocal strain gradient model will be developed to determine the size effects and the small scale parameters will be identified for SLGS based on experimental data. A comprehensive parametric study will be focused on the effect of the thermal and hygroscopic distributions (temperature and moisture), physical loads (in-plane magnetic field), visco-Pasternak substrate parameters (spring constant, shear layer parameter and damping constant), small scale parameters (lower and higher order nonlocal parameters and material characteristic parameter) on the wave frequency and phase velocity of SLGS.

2. Problem formulation

The paper is focused on the modeling of a substrate-supported graphene sheet in hygrothermal environment under in-plane magnetic field. Fig. 1 shows a schematic diagram of a set of viscoelastic SLGS in the rectangular shape embedded within a visco-Pasternak foundation in the hygrothermal environment. The visco-Pasternak medium introduced by spring constant (k_W), shear layer parameter (k_G) and damping constant (c_D) account for the effects of normal, transverse shear and damping loads, respectively. Furthermore, an in-plane magnetic field is applied on the upper surface of the orthotropic nanoplate. The primary target of the current paper is to formulate mentioned conditions in an agreeable fundamental equation for the investigations.

For studying wave propagation, it is assumed that the waves do not reach the boundary conditions (the case is well-known as bulk waves with the application in nondestructive tests), so the example will be discussed without considering the boundary conditions. Under such case, the nonlocal integral-type formulation will be always equivalent to the nonlocal differential-type model [37,72]. It is also assumed that geometrical and physical specifications of the nanoplate are with uniform thickness h, length a, width b, Poisson's ratios υ_{12} and υ_{21}, mass density ρ, and Young's modulus in the x-y plane (E_1 and E_2).

2.1. Bi-Helmholtz nonlocal strain gradient theory

Lim et al. [31] proposed the nonlocal strain gradient theory to