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Wave dispersion of mounted graphene with initial stress

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ABSTRACT

This paper is focused on the initial stress affected wave dispersion in mounted graphene. To capture the size-dependent and shear deformation effects, the second-order shear deformation theory (SSDT) and nonlocal strain gradient elasticity theory are used to model the graphene. A size-dependent shear deformation plate model is established on the basis of the orthotropic constitutive equations, the nonlocal strain gradient theory as well as the SSDT. Analytical solutions are developed for the wave frequency and phase velocity. The influences of small-scale parameters, initial stress and elastic medium on wave propagation behaviors of the graphene sheets are explored. It is found that the developed model reasonably interprets the softening effects of flexural frequencies and phase velocities. Unlike the classical (scaling-free) model, the developed size-dependent model shows a reasonably good agreement with the experimental frequencies and phase velocities. The wave frequencies and phase velocities of single layer graphene sheets (SLGS) will decrease with increasing compression load, and can increase by increasing tension load. The developed size-dependent 2D continuum model is hopeful to provide a possible theoretical approach to explore the wave behaviors of Graphene-like 2D materials.

1. Introduction

Due to wonderful physical and mechanical properties, single layer graphene sheet (SLGS) has received significant attention from researchers and engineers [1]. With the development of the nanodevices and nanotechnology, SLGS are now one of the usage components in many fields such as nano-electromechanical system (NEMS) [2]. Hence, accurate prediction of nanostructures vibration specifications becomes obligatory for fundamental researches and engineering designs. Often, experimental, molecular dynamic simulation and continuum mechanic approaches were used for analysis of nanostructures. On one hand, because of its simplicity and accuracy, continuum mechanics approaches are more common to use for predicting the mechanical behaviors of nanostructures in the large scaled systems. On the other hand, classical continuum mechanic theories cannot consider the size effects alone. Experimental and molecular dynamic approaches have showed that size effect plays an important role when structures become small. To fix this drawback, researchers suggested new micro and nano continuum theories, such as the strain gradient elasticity theory [3], the nonlocal elasticity theory [4,5] and the couple stress theory [6].

The nonlocal stress is assumed as a convolution integral over a nonlocal kernel function. It makes the governing equations be complicated integro-differential equations. An approximate differential-type constitutive relation was therefore suggested for a specified kind of kernel function [7]. Owing to the simplicity of differential-type constitutive relation, many nonlocal differential-type models have been recently developed to be applied for studying the scaling effects on the static and dynamic behaviors (such as free and force vibration, buckling, and dispersion of elastic waves) of rods [8–11], beams [12–16] and plates [17–24]. Moreover, a critical review of the static and dynamic behavior of nanobeams via nonlocal elasticity theory is suggested by Eltaher et al. [25]. Nevertheless, it has been pointed out by a large number of studies that the paradox or inconsistency appeared in the mechanical behaviors of one-dimension (1D) problems modeled on the basis of nonlocal differential-type constitutive relation [26–29,16,30]. This is because these problems were analyzed with having to involve boundary conditions. It has been reported that these problems with having to involve boundary condition have certain boundary conditions between the nonlocal differential and integral formulations, see e.g., [31,32,27]. Recently, it was shown by Romano et al. [33,34] that, in nonlocal elastic problems on bounded structural domains, Eringen nonlocal integral model [7] leads to ill-posed problems since the stress field outputted by the strain-driven nonlocal constitutive relation is incompatible with equilibrium requirements. Ill-

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posedness can be partially addressed by adopting a local-nonlocal mixture model for the strain-driven law [31,32,27,35,36], as comprehensively discussed in [37]. The new stress-driven model, first proposed in Romano and Barretta [38], is able to overcome the intrinsic inconsistency of the strain-driven nonlocal theory of elasticity. For wave propagation studied here, we assume that in-plane waves do not reach the boundary conditions of nanoplates. That is, in comparison of wavelength, nanoplates may be viewed as infinite. Thus, the problem will be analyzed without considering the boundary conditions. Under such case, the nonlocal integral formulations are equivalent to the nonlocal differential models [36].

In Eringen nonlocal theory, the size effects are obtained via assuming the stress at a material point in a domain as a function of not only the strain at that material point but also the strains at all other material points in that domain. However, this theory cannot satisfy all of the mechanical problems of graphene sheets. Hence, in the other theories, strain gradient theory plays the same role to capture of size effects. The strain gradient theory may be referred to as stress-driven nonlocal models since the strain of a material point depends on the stresses in all material points of the domain. The strain gradient elasticity theory has been applied to analyze the mechanical behavior of plates by Karami and Janghorban [39]. In recent years, owing to the rapid growth of micro and nano-technology, the size-dependent elasticity theory needs to be improved. Alternatively, the nonlocal strain gradient theory has been developed by combining of the Eringen nonlocal elasticity theory and strain gradient theory, which is earlier suggested in Aifantis [40] and has been recently used in the literature [29,41–43]. Until 2015, Lim et al. [44] showed that the nonlocal strain gradient theory takes more accuracy results in comparison with nonlocal elasticity theory, especially in wave propagation problems. In the following, this theory has been recently frequently-used in various mechanical problems such as wave propagation, vibration, bending and buckling [45–64]. It was recently reported by Zhu and Li [36] that the nonlocal strain gradient theory may merely be referred to as a combination of the strain-driven and stress-driven nonlocal theories.

Recently, many researchers used the nonlocal strain gradient theory to study the wave propagation in mechanical structures. Ebrahimi and Dabbagh [65] proposed a basic report about the influence of nonlocal and strain gradient parameter on the flexural wave propagation responses of functionally graded nanoplates. They investigated the effects of external works (such as magnetic potential, electric voltage and material distribution in the absence and presence of both length scale parameters) via refined shear deformation plate theory. According to their results, these parameters can change the effect of external works on the values of the wave frequency and phase velocity of nanoplates. The influence of the magnetic field on the wave propagation of functionally graded nanoplate based on the nonlocal strain gradient theory was studied by Karami et al. [66]. In addition, Nami and Janghorban proposed an analytical solution 3D elasticity for investigating bulk waves of orthotropic nanoplates using nonlocal elasticity theory [67]. This work is a useful guide to understand the wave behaviors of the whole range of graphene sheets.

In view of all articles that have been said so far, very few studies have tried to propose the model for analysis of orthotropic nanoplates via nonlocal strain gradient theory. Owing to the natural orthotropic property of SLGS, the orthotropic constitutive equations should be taken into account to develop high-precision plate models for SLGS. To capture the size-dependent and shear deformation effects, the second-order shear deformation theory (SSDT) and nonlocal strain gradient elasticity theory will be used to model the graphene. It will be reported that, the developed model reasonably interprets the softening effects of flexural frequencies and phase velocities, and shows a reasonably good agreement with the experimental frequencies and phase velocities. Furthermore, the influences of small-scale parameters, initial stress and elastic medium on wave propagation behaviors of the graphene sheets will be explored.

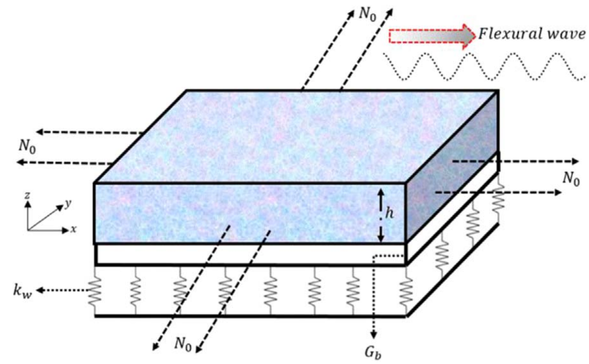

Fig. 1. The configuration of flexural wave propagation in an orthotropic nanoplate with initial stress mounted on an elastic medium.

2. Theoretical formulations

This study considers SLGS modeled by using an orthotropic nanoplate theory. The configuration of flexural wave propagation in an orthotropic nanoplate with initial stress mounted on an elastic medium is shown in Fig. 1. This structure is subjected to the initial stresses created by compressive and tension loads while mounted on an elastic medium. The foremost purpose of this article is to analyze the flexural wave behaviors of SLGS in the mentioned situations.

To study the size-dependent flexural wave behaviors, we suppose that the waves do not reach the boundary conditions of SLGS. That is to say, SLGS may be viewed as a relatively large nanoplate in comparison of wavelength of interest. Under such case, the flexural wave behaviors will be analyzed without boundary conditions.

2.1. Second-order shear deformation theory (SSDT)

Extensive studies have been carried out by using classical plate theory (CPT or the Kirchhoff-Love theory) and first-order shear deformation theory (FSDT). Owing to omitting shear deformations and rotary inertia, the CPT leads to unreliable results for thick and moderately thick plates, which can be improved by considering the FSDT since it contains a shear correction factor. However, the suitable value of the shear correction factor, which is dependent on the variation of Poisson's ratio, geometry, loading and boundary conditions, is often difficult to predict. To this end, many higher-order-shear-deformation theories (HSDTs) [68–71] have been presented since they do not need a shear correction factor and provide the best accuracy than the CPT and FSDT.

In this section, the equations of motion for investigating wave propagation in orthotropic nanoplates on the basis of the SSDT are derived, and then they can be solved analytically to find the wave dispersion. According to the SSDT [72,71], the displacement components of the orthotropic nanoplates can be written as

$$u_1 = u + zQ_1 + z^2Q_2,\ \ u_2 = v + z\psi_1 + z^2\psi_2,\ \ u_3 = w(x, y), \tag{1}$$

where (u_1, u_2, u_3) are the displacements in directions (x, y, z), respectively. The above displacement components are functions of position (x, y) and time (t), but all displacement components can be represented by $(u, v, w, Q_1, Q_2, \psi_1, \psi_2)$.

By applying the displacement components (1), the strain-displacement relation can be given by

$$\{\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}\} = \left\{\varepsilon_{xx}^0, \varepsilon_{yy}^0, \gamma_{xy}^0\right\} + z\{K_{xx}, K_{yy}, K_{xy}\} + z^2\{K'_{xx}, K'_{yy}, K'_{xy}\},$$
$$\{\gamma_{yz}, \gamma_{xz}\} = \left\{\gamma_{yz}^0, \gamma_{xz}^0\right\} + z\{\gamma'_{yz}, \gamma'_{xz}\}, \tag{2}$$