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Nanoscale vibration characteristics of multi-layered graphene sheets

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ABSTRACT

A continuum-based plate model is proposed to study the nanoscale vibration characteristics of multi-layered graphene sheets (MLGSs) that are increasingly being proposed for important engineering applications such as THz resonators. Generalized Differential Quadrature (GDQ) method is used to predict the natural frequencies and their associated vibration modes of single-layered and triple-layered graphene sheets, as well as general MLGSs. Numerical simulations are carried out to examine the effects of van der Waals (vdW) interactions, which are present as bonding forces between the layers, on nanoscale vibration natural frequencies and their mode shapes. The results show that for a general MLGSs, vibration modes can be classified into 3 families—lower classical synchronized modes which are independent of van der Waals forces, middle van der Waals enhanced modes which are largely determined by the presence of van der Waals interactions and higher mixed modes which are combinations of the classical synchronized modes and van der Waals enhanced modes. Detailed characterizations of these modes from their derived mode shapes have been achieved for the typical case of triple-layered GSs, as well as general MLGSs. Effects of different boundary conditions, aspect ratios and the number of layers on nanoscale vibration properties have been examined in detail. The results presented in this paper, for the first time, provide accurate and wholesome studies and characterizations on the interesting nanoscale vibration properties of multi-layered graphene sheets and the results obtained will certainly be useful to those who are concerned with the dynamics of graphene sheets which are increasingly being deployed for various innovative engineering applications.

1. Introduction

Carbon nanotubes (CNTs) and graphene sheets (GSs) are two allotropes of carbon in different spatial presentations. Ever since their discovery in 1991 by Sumio Ijima of the NEC Laboratory in Tsukuba, Japan [1], there has been intensive research on the potential applications of these unique nanostructural elements. This interest stems from the fact that these elements hold substantial promise as building blocks for nanoelectronics, nano-sensing, nano-actuating devices and super-strength nano-composites [2–6] because of their super physical, chemical and electronic properties. Among many applications of CNTs and GSs, mechanical properties need to be determined and extensive research has been carried out to establish these properties accurately and reliably. Since controlled experimental characterizations at nanoscale are still difficult to achieve to date, various analytical/numerical methods of prediction have been rigorously pursued recently. These methods can be roughly classified as atomistic-based methods and continuum-based methods.

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Atomistic-based methods such as the classical molecular dynamics simulation [7,8], tight-binding molecular dynamics [9] and density function theory [10] have been employed to study rigorously mechanical properties of CNTs and GSs in static bending, dynamic vibration and buckling behavior. However, these simulation methods remain formidably expensive in computational requirement, even with today's computational efficiency and speed. As a result, researchers in this area have been constantly searching for more efficient computational methods which can be used to analyze CNTs and GSs. Recently, researchers have increasingly turned their attentions to the much more familiar continuum structural mechanics models with the promise that these can be applicable to nanoscale structural components such as CNTs and GSs. Alongside with these thoughts, many continuum structural mechanics models have been proposed during the last decade. These include the beam modeling proposed by Govindjee and Sackman [11] and Yoon et al. [12], the cylindrical shell model proposed by Ru et al. [13–16] and the space truss model by Li and Chou [17,18].

With reference to vibration analysis of GSs which is the main interest of this paper, a number of different methods have been developed during recent years. Detailed vibration analysis based on continuum mechanics as well as molecular mechanics has been carried out by Chowdhury et al. [19]. Based on non-local elasticity and higher order shear deformation theory, vibration modes of single graphene sheets were established [20]. When embedded on elastic foundation, dynamics properties of single layer graphene sheet were examined and the effect of elastic foundation assessed by Murmu and Pradhan [21]. Pradhan [22] also examined the small scale effect on vibration characteristics of embedded multi-layered graphene sheets. Taking into account geometrical nonlinearities, large amplitude vibration of multi-layered graphene sheets was studied by Jomehzadeh and Saidi [23]. Based on the assumption that the single layered graphene sheets are orthotropic, Pradhan analyzed the vibration problems under elastic support and non-local elasticity [24,25]. However, most of these existing work either assumed single layer of graphene sheet in which van der Waals is non-existent or were based on the classical assumed mode shape approach, as a result, results obtained to date have not been that satisfactory. In this paper, a general continuum-based plate model is proposed to study the nanoscale vibration characteristics of multi-layered graphene sheets (MLGSs) that are increasingly being proposed for important engineering applications such as THz resonators. Generalized Differential Quadrature (GDQ) method is used to predict the natural frequencies and their associated vibration modes of single-layered and triple-layered graphene sheets, as well as general MLGSs. Numerical simulations are carried out to examine the effects of van der Waals (vdW) interaction, which is present between the layers, on nanoscale vibration natural frequencies and their mode shapes. The results show that for a general MLGSs, vibration modes can be classified into 3 families—lower classical synchronized modes which are independent of van der Waals forces, middle van der Waals enhanced modes which are largely determined by the presence of van der Waals interactions, and higher mixed modes which are combinations of the classical synchronized modes and van der Waals enhanced modes. Detailed characterizations of these modes from their derived mode shapes have been achieved for the typical case of triple-layered GSs, as well as general MLGSs. Effects of different boundary conditions, aspect ratios and the number of layers on nanoscale vibration properties have been examined in detail. The results presented in this paper, for the first time, provide accurate and wholesome studies and characterizations on the interesting nanoscale vibration properties of multi-layered graphene sheets and the results obtained will certainly be useful to those who are concerned with the dynamics of graphene sheets which are increasingly being deployed for various innovative engineering applications.

2. Equations of motion

Consider in general a MLGS that is supported with given boundary conditions. The chemical bonds are assumed to be formed between the GSs which are the van der Waals forces. The MLGSs is modeled as a stack of plates of length of each plate a, width b, thickness h, mass density ρ, and Young's modulus E, as shown in Fig. 1.

In the general case of L layered graphene sheets, each layer can be closely modeled as a plate with the chemical bonding forces between the layers to be modeled as pressure force applied to each of the layers, the L coupled equations of motion

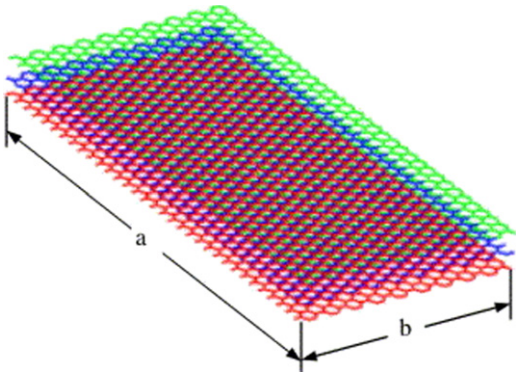

Fig. 1. A multi-layered graphene sheets.