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Decoupling the nonlocal elasticity equations for thermo-mechanical vibration of circular graphene sheets including surface effects

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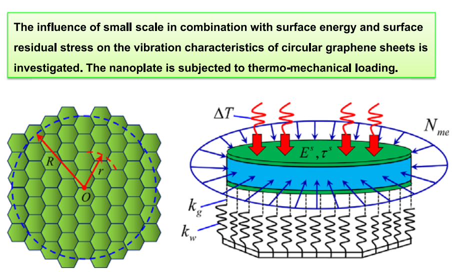
HIGHLIGHTS

- Vibration analysis of circular graphene sheets under thermo-mechanical loading.
- Both surface and nonlocal effects are taken into account.
- Equation of motion is derived by decoupling the nonlocal constitutive equations.
- Size effects increase by increasing the amount of surface residual stress.

GRAPHICAL ABSTRACT

The influence of small scale in combination with surface energy and surface residual stress on the vibration characteristics of circular graphene sheets is investigated. The nanoplate is subjected to thermo-mechanical loading.



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ABSTRACT

This article deals with the axisymmetric vibration properties of circular single-layered graphene sheet embedded in a polymer matrix under thermo-mechanical loading. Both surface and nonlocal effects are taken into account. To this end, Gurtin–Murdoch continuum elasticity in conjunction with the nonlocal elasticity theory is used to develop a modified continuum plate model for free vibration analysis of the nanoplates. The governing equations are derived by decoupling the nonlocal constitutive equations of Eringen theory in the polar coordinate. Galerkin's method is used to obtain the vibration frequencies. To verify the accuracy of the Galerkin results, a differential quadrature (DQ) solution is also developed. Galerkin results are successfully verified with those of the DQ method. A good agreement is also found between the present results and experimental data. Further, in comparison to the available molecular dynamics simulation results, the present formulation with appropriate values of surface and nonlocal parameters provides more accurate results than those by the classical plate model.

1. Introduction

The superior mechanical, chemical and electronic properties of nanostructures make them favorable for nanoengineering applications. Recently, Stankovich et al. [1] have developed a process for the obtaining single-layered graphene sheets (SLGSs) from graphite. Graphene sheets are one of the most important nanosized structural elements which are commonly used as components in micro-electro-mechanical systems (MEMS) and nano-electro-mechanical systems (NEMS) [2,3]. Furthermore, it has been revealed that adding graphene sheets to polymer matrix could greatly improve the mechanical properties of the host polymer [4]. In addition, nanostructures such as armchair carbon nanotubes and nanoplates have shown significant potential applications in the field of environmental technologies [5]. Nanomechanical resonators are one of most important NEMS devices which have

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received increasing attention from the scientific community in recent years [6–9]. The nanomechanical resonators may operate at very high frequencies up to gigahertz range [10]. It has been reported that the resonant frequencies of a resonator with length L are proportional to L^{-2} [7]. Therefore, very high frequencies (VHF) can be achieved by reduction in the size of the resonator. In addition, the resonant frequency greatly affects the mass detection ability of a resonator. As the resonant frequency increases to very high values, the ability of the resonator to sense small molecules increases [11]. This leads to potential applications in the early diagnosis of diseases including cancer [12]. Yang et al. [13] first showed that VHF nanoelectromechanical systems provide unprecedented sensitivity in measuring molecular weight. The nanomechanical resonators can also be used for the label-free detection of amyloid growth [14], the measurement of mass, density, and volume during the cell cycle of yeast [15], and the detection of physical quantities such as quantum state [16], spin [17] and force [18]. Another important potential application of nanoresonators is the actuation and detection of NEMS motion. Some available techniques for this purpose have been introduced and the accuracy, bandwidth, and robustness of these techniques have been discussed in detail in the review paper of Ekinci [6]. Arlett et al. [8] reviewed micro- and nanoscale biosensors including suspended microchannel resonators (SMRs) and optical microring resonators (MRRs). In another work, it has been reported that nanoelectromechanical systems are ideal candidates for studying quantum behavior of macroscopic objects [9]. For more information about the nanomechanical resonators and their applications in biological/chemical detection, the reader is referred to the paper by Eom et al. [7]. They anticipated that further research will be done on the experiments, theories, and computational simulations to understanding the dynamic behavior of NEMS resonators especially those used for sensing nano-objects. Graphene sheet can be used as a building block for nanoresonators with high or ultra high frequencies [2]. Thus, understanding the mechanical behavior of single-layered graphene sheets is an important problem. Dai et al. [19] studied the nonlinear vibration behavior of graphene resonators. Their study suggests the design principles of a graphene resonator as a mass sensor. A nonlinear finite elasticity theory has been developed for the graphene resonators, both for elastostatics and elastodynamics problems by Atalaya et al. [20].

Modified continuum models have been widely used for the analysis of various dynamic and stability problems at small scales. The main reasons for this are that controlled experiments on nanoscale are difficult to perform and molecular dynamic (MD) simulations are highly computationally expensive for nanostructures with large numbers of atoms or molecules inside them. There are various modified classical continuum theories which capture size effects such as couple stress theory [21], strain gradient elasticity theory [22], modified couple stress theory [23] and nonlocal elasticity theory [24,25]. Among all size-dependent theories, the nonlocal elasticity theory has been commonly applied in the theoretical investigations of structures at small scale [26–34]. Nonlocal theory of Eringen is based on this assumption that the stress tensor at an arbitrary point in the domain of nanomaterial depends not only on the strain tensor at that point but also on strain tensor at all other points in the domain. Both atomistic simulation results and experimental observations on phonon dispersion have shown the accuracy of this observation [24]. Based on lattice dynamics and molecular dynamics (MD) simulations, Chen et al. [35] provide an atomic viewpoint to study micro-continuum field theories, including micro-morphic theory, micro-structure theory, micro-polar theory, Cosserat theory, nonlocal theory and couple stress theory, and reported that the nonlocal continuum models are reasonable from a physical point of view. Furthermore, Ansari et al. [36] have shown that the nonlocal elasticity theory is quite accurate and reliable for the free vibration analysis of SLGSs by employing molecular dynamics modeling. In another work, Farajpour et al. [37] reported that the results of nonlocal plate theory with consideration of surface effects are in good agreement with those of MD simulations for the buckling of circular single-layered graphene sheets.

A review of literature shows that compared to rectangular graphene sheets, few research works have been reported on the continuum based analysis of graphene sheets of circular shape especially for the mechanical behavior taking into account the effect of surface energy. Duan and Wang [38] presented an exact closed-form solution for the axisymmetric bending of circular graphene sheets via nonlocal plate model. Aghababaei and Reddy [39] developed a nonlocal third-order shear deformation plate theory for the vibration, bending and buckling of the SLGSs. Furthermore, Malekzadeh et al. [40] investigated the small scale effect on the thermal buckling of orthotropic arbitrary straight-sided quadrilateral nanoplates. Wang et al. [41] investigated the small scale effects on the longitudinal wave propagation in nanoplates. In another work, Jomehzadeh and Saidi [42] presented an exact solution for three dimensional vibration analysis of nanoplates by decoupling the field equations of Eringen theory. The Levy type method and nonlocal plate model have also been used in the vibration and buckling analyses of nanoplates [43]. Farajpour et al. [44] also studied the axisymmetric buckling of nanoscale circular plates under uniform radial compression via nonlocal elasticity theory. Dynamic response of a nanoplate subjected to a moving nanoparticle was examined within the context of nonlocal continuum theory by Kiani [45,46]. Wang et al. [47] reported thermal buckling properties of rectangular nanoplates with small-scale effects. They derived the critical temperatures for the nonlocal Kirchhoff and Mindlin plate theories by nonlocal continuum mechanics. From their work, it can be concluded that the small-scale effects are significant for the thermal buckling properties of nanoplates. Linear buckling response of orthotropic SLGS under linearly varying in-plane load via the nonlocal elasticity theory is also discussed in the literature [48]. These interesting research works are limited to ultrathin films without surface layers. It is well-known that the influence of surface properties on the static and dynamic responses of structures is negligible compared with the bulk energy effect in the classical elasticity theory (CPT). The surface energy of an elastic solid is related to a few layers of atoms near its surface. Hence, the ratio of surface energy to bulk energy is extremely small at large scale. However, reduction in the structural size to micro/nanometer regime leads to a significant increase in the surface-to-bulk energy ratio [49,50]. Thus, in order to correctly predict the mechanical behavior of micro/nano-structural elements such as nanowires [51], carbon nanotubes (CNTs) [52] and nanoplates [53], surface effects should be taken into account when non-classical continuum models are developed using the nonlocal elasticity theory. Recently, Assadi and Farshi [53] investigated the size dependent stability of circular nanoplates with consideration of surface properties. However, they have not taken into consideration the influence of nonlocality on the buckling characteristics in their model. Based on the nonlocal theory of Eringen, Wang and Wang [54] studied the vibration behavior of nano-scale plates with consideration of surface effects. They obtained closed form solutions for the natural frequencies of simply supported Kirchhoff and Mindlin nanoplates of rectangular shape.

To the best of authors' knowledge, the nonlocal and surface effects on the vibration characteristics of circular nanoplates in an elastic medium under thermo-mechanical loading are not investigated in the open literature. This motivates us to investigate this problem here. The surrounding elastic medium is modeled as Pasternak-type elastic foundation. The non-classical governing