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Surface effect on the large amplitude periodic forced vibration of first-order shear deformable rectangular nanoplates with various edge supports

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ABSTRACT

Surface stress and surface inertia effects may play a significant role in the mechanical characteristics of nanostructures with a high surface to volume ratio. The objective of this study is to present a comprehensive study on the surface stress and surface inertia effects on the large amplitude periodic forced vibration of first-order shear deformable rectangular nanoplates. To this end, the Gurtin–Murdoch theory, first-order shear deformation theory (FSDT) and Hamilton's principle are employed to develop a non-classical continuum plate model capable of taking the surface stress and surface inertia effects and also the rotary and in-plane inertias into account. To solve numerically the geometrically nonlinear forced vibration of nanoplates with different boundary conditions, the generalized differential quadrature (GDQ) method, numerical Galerkin scheme, periodic time differential operators and pseudo arc-length continuation method are employed. The effects of parameters such as thickness, surface residual stress, surface elasticity, surface mass density, length-to-thickness ratio, width-to-thickness ratio and boundary conditions on the nonlinear forced vibration of rectangular nanoplates are fully investigated. The results demonstrate that surface effects on the nonlinear frequency response of aluminum (Al) nanoplate are more prominent in comparison with the silicon (Si) nanoplate.

1. Introduction

The rapid advances in nanoscience and nanotechnology have led to the rapidly developments in fabrication of Nano- and Micro- Electro-Mechanical Systems (NEMS and MEMS) in recent years, due to their superior mechanical and physical properties. Such small-size structures have been widely utilized in many fields, namely optics, aerospace technology, electronics, chemistry, mechanical engineering and biomedical engineering [1–3]. Nanowire, nanobeam, nanoplate and nanoshell are the elementary building blocks in MEMS and NEMS. In order to design, fabricate and develop such nanostructures, it is necessary to study all crucial characteristics of their mechanical behaviors. Therefore, a variety of studies have been carried out on the prediction of mechanical characteristics of nanostructures [4–13]. For example, Ansari et al. [14] presented a size-dependent Timoshenko beam model on the basis of surface stress elasticity theory to study the surface effects on the geometrically nonlinear forced vibration characteristics of nanobeams with various edge conditions. Setoodeh et al. [15] developed a nonlocal Mindlin plate model to investigate the geometrically nonlinear vibration of orthotropic graphene sheets. Moreover, Shen et al. [16] examined the nonlinear vibration of bilayer graphene sheets in thermal environments

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employing the molecular dynamics simulations and nonlocal elasticity.

Some atomistic and molecular dynamics simulations and experimental studies have demonstrated that the mechanical characteristics of nano- and micro- structures are size-dependent and behave in a different way from their macroscale counterparts [17–20]. On the other hand, the classical continuum mechanic is not able to predict and explore the size-dependent mechanical characteristics of structures at micro- and nano-scales. Therefore, several investigations have been performed to develop the non-classical continuum theories such as nonlocal elasticity [21], strain gradient elasticity theory [22], modified strain gradient elasticity [19], modified couple stress theory [23] and surface stress elasticity theory [24,25] which are capable of incorporating the size-effects into account. Among different non-classical continuum theories, the surface stress elasticity theory has been adopted in many investigations to investigate the effects of surface stress and surface inertias on the mechanical behavior of nanostructures. The surface stress effect is particularly important in nano-scaled solids or structures with high surface-to-volume ratios. Moreover, the positive/negative surface stresses lead to inducing a compressive/tension residual stress fields in bulk part of nanostructures, respectively [25–27]. The compressive residual stress fields may be leads to a self-instability in the nanostructures even in the absence of external mechanical loadings [28]. Therefore, to avoid the self-instability of nanostructures, the critical size of nanostructures should be determined.

A very elegant mathematical formulation within the framework of continuum mechanics was developed by Gurtin and Murdoch [24,25] to include the surface stress and interfacial energy into classical continuum theories. On the basis of proposed model, the surface surfaces are simulated as layers with zero thickness and different material properties from the bulk layer. Later, various researchers developed the size-dependent nanobeam, nanoplate and nanoshell models incorporating the surface stress effects to predict the static and dynamic mechanical behaviors of nanostructures [28–33]. For example, Wang and Feng [34] presented a size-dependent Timoshenko beam model to study the surface effects on the axial buckling and the transverse vibration of nanowires. They included that the positive surface elastic constants lead to an increase in the critical buckling loads and natural frequencies. Assadi and Farshi [35] modified the classical Kirchhoff's circular plate model to include the effects of surface properties on the vibration characteristics of circular nanoplates. It observed that surface stress effect on the natural frequencies and mode shapes is more prominent in larger and thinner circular nanoplates. Ansari et al. [36] developed a non-classical circular plate model to investigate the vibrational response of circular nanoplates considering surface energies. Based on the Kirchhoff plate theory, Hasheminejad and Gheshlaghi [37] adopted a dissipative surface stress model to illustrate the surface dissipation effect on the quality factor and natural frequencies of elastic nanofilms. Utilizing a nonclassical geometrically nonlinear beam model on the basis of the Euler–Bernoulli theory, Wang and Wang [38] performed a study on the non-linear pull-in instability of nano-switches and discovered that surface energy effects on the pull-in voltage depends on the geometric parameters such as length, height and initial gap of the nano-switch. Ansari et al. [39] examined the surface effects on the free vibration characteristics of circular nanoplates in the vicinity of postbuckling domain based on a newly developed nonlinear circular Mindlin nanoplate model and numerical solution procedure.

To the authors' knowledge, the surface stress and surface inertia effects on the geometrically nonlinear forced vibration of nanoplates have not been investigated. Moreover, the influences of the transverse shear deformation and rotary inertia become more prominent for the thick and moderately thick nanoplates. Therefore, in this paper, a non-classical first-order shear deformable rectangular plate model is developed on the basis of Gurtin–Murdoch theory using a variational procedure. The new developed plate model incorporates the surface stress and surface inertia effects and can capture the small-scale effect, unlike the classical first-order shear deformable plate model. The newly developed non-classical plate model is employed to investigate the nonlinear forced vibration of nanoplates with various boundary conditions employing the generalized differential quadrature (GDQ) method, numerical Galerkin scheme, periodic time differential operators and pseudo arc-length continuation method.

The rest of the paper is organized as follows. In Section 2, a new non-classical model for a first-order shear deformable plate is developed on the basis of Gurtin–Murdoch theory, Hamilton's principle and a variational approach. Also, by defining the appropriate non-dimensional parameters the governing equations are expressed in the non-dimensional form. In Section 3, the geometrically nonlinear forced vibration problem of a rectangular nanoplate is numerically solved by means of the GDQ method, numerical Galerkin scheme, periodic time differential operators and pseudo arc-length continuation method. In Section 4, the numerical results are presented to quantitatively show the effect of parameters such as thickness, surface residual stress, surface mass density and boundary condition on the large amplitude periodic forced vibration of rectangular nanoplates. Also, the differences between the results given by the current non-classical plate model and classical counterpart are shown. The concluding remarks are given in Section 5.

2. Mathematical formulation of governing equations and boundary conditions

As shown in Fig. 1, consider a uniform rectangular nanoplate with length a, width b and thickness h subjected to a harmonic excitation transverse force $F(t)$. Introducing the Cartesian coordinate system on the middle-plane of nanoplate, the upper $\left(z=\frac{h}{2}\right)$ and lower $\left(z=-\frac{h}{2}\right)$ surface layers are symbolized by S^+ and S^-, respectively. According to the first-order shear deformation theory (FSDT), the components of displacement field (u_x, u_y, u_z) of