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Original Research Article

Vibration analysis of nanotubes based on two-node size dependent axisymmetric shell element

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ABSTRACT

In this paper, size dependent axisymmetric shell element formulation is developed by using the modified couple stress theory in place of classical continuum theory. Since the study of nanoshells is conducted in nanodimensions, the mechanical properties of nanoshells are size dependent; therefore, taking into consideration the size effect, nonclassical continuum theories are used. In the present work the mass–stiffness matrix for axisymmetric shell element is developed, and by means of size-dependent finite element, the formulation is extended to more precisely account for nanotube vibration. It is shown that the classical axisymmetric shell element can also be defined by setting length scale parameter to zero in the equations. The results show that the rigidity of the nanoshell in the modified couple stress theory is greater than that in classical continuum theory, which leads to the increase in natural frequencies. The findings also indicate that the developed size dependent axisymmetric shell element is able to cover both cylindrical and conical shell elements and is reliable for simulating micro/nanoshells. Using size dependent axisymmetric shell element increases convergence speed and accuracy in addition to reducing the number of the required elements.

1. Introduction

In all applications of the nanostructure in sciences, size effects play a significant role in proper study of the behavior of such structures [1]. According to the weak of classical continuum to incorporate size effect of micro/nanoscales, today, many researchers use higher order theories such as the modified couple stress theory and strain gradient theory to model micro/nanocomponents [2].

Classical couple stress theory was developed with considering higher order rotation gradient as a deformation matrix which excludes the symmetric part of the second order deformation gradient by Mindlin and Tiersten [3]. Classical couple stress theory consists of couple of length scale parameters, which are difficult to determine. Therefore Yang et al. [4] proposed modified couple stress theories in which a new additional equilibrium equation and the equilibrium of the couples of moments, besides classical equilibrium equations of forces and their moments, exist and lead to one length

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scale parameter. The strain gradient theory was presented by Fleck and Hutchinson [5]. According to this theory, the stretch gradient and rotation gradient tensors are taken into account as the constitutive parts of the second-order deformation tensor. Afterwards, the modified strain gradient theory, which has three length scale parameters and considered only the symmetric parts of strain gradient in the equations, was proposed by Lam et al. [6]. These three parameters can be combined and reduced to only one single measurable parameter under the assumptions of modified couple stress theory.

Many studies have employed modified couple stress theory and modified strain gradient theory. Using Timoshenko beam model and modified couple stress theory, Ma et al. [7] investigated the formulation of axial and transverse deformation of microstructures. Using Euler–Bernoulli beam model and modified couple stress theory, Akgöz et al. [8] examined the vibration frequency of non-homogenous and non-uniform micro-beams. In another study, using modified couple stress theory, Reddy [9] examined the bending of axisymmetric circular plates, demonstrating the possibility of the use of the equations developed for extending the analytical response to free vibrations, bending, and buckling of linear cases. Tadi Beni et al. [10] investigated the size dependent pull-in instability of rotational nano-mirror using modified couple stress theory and found good consistency between experimental results and the new theory as compared to the classical theory. Karimi Zeverdejani et al. [11] investigated the nonlinear vibration of the microtubule through strain gradient theory and showed that the effect of the material length scale parameter on microtubule vibration was considerable. Wang et al. [12] studied the free vibration and static bending of Timoshenko beam by using strain gradient theory. They showed that the effect of size parameter on the natural frequency is considerable. Also, Zhao et al. [13] investigated nonlinear vibrations, buckling and static bending of Euler–Bernoulli beam by using strain gradient theory.

In order to correctly predict the behavior of micro/nanostructures, in addition to considering the length scale parameter, it is also necessary to use an appropriate geometric model to correctly model structures and elements. As mentioned many researchers have so far used beam model in order to model nanotubes. Due the increasing use of elements in the shape of axisymmetric shells, such as single wall carbon nanotubes (SWCNTs), in the nano-scale, it is essential to model such elements more exactly. By using the axisymmetric shell model instead of the beam model, the new formulation could be carry out more exact and real simulation of geometrical shapes and hence it is suitable for use in the nano-scale. Prevalently, researchers have recently used the shell model to model the SWCNT in a more appropriate way [14]. Furthermore, due to the complexity of micro/nanostructures such as complicated loading or geometry, the use of analytical method is not always possible, it is especially important to use other current methods such as finite element method (FEM), which provides an alternative approach. Xia and Hutchinson [15] introduced displacement derivatives as additional parameters at each node. Chyuan [16] used the finite element method to investigate the levitation of micro electro mechanicals (MEMS) comb-drive. Zervos [17] studied the size effect and localization of the deformation in thick-walled cylinder by using an existing displacement function of 18-degree of freedom (DOF) thin plate element. Metz et al. [18] investigated the bending behavior of conducting polymer electromechanical actuators using the numerical method. Tajalli et al. [19] investigated the dynamic pull-in of electrostatically actuated micro/nanoplate by using the nine-node plate element and by calculating the nonlinear geometry and pressure of fluid.

It should be noted that most of these studies have been conducted on the basis of the classical continuum theory. However, as mentioned previously, not only does classical continuum theory underestimate the stiffness of micro/nanostructures, but it also excludes size effects in predicting the behavior of micro/nanostructures. Hence, it is unable to correctly predict the behavior of micro/nanostructures.

Since experimental results have shown that mechanical properties in beam type nanostructures are size dependent, researchers are seeking to investigate this dependence on other nanostructures as well. On the other hand, since testing is the most accurate way to examine the mechanical properties of the nano-scale, it is difficult to control the test on this scale, which has led researchers to look for other methods for modeling. Perhaps, after conducting the testing of methods such as molecular dynamic (MD), these methods have high computational costs and are not suitable for nanostructures with high atomic numbers, such as long nanotubes. Therefore, researchers have used non-classical continuum mechanical methods that can measure the effect size in recent years as an alternative method. It should be noted that these models lead to nonlinear and coupling governing equations for structures like nano-tubes, which should be used to solve appropriate low-error methods. Recently, semi-analytic and numerical methods have been presented in the literature. According to the above, the authors in this paper use finite element method with the definition of a new size dependent element in order to compensate for the shortcomings of the above methods and reduce the cost of the calculations and increase the accuracy of the results as well as the dependence on the size in modeling the nano-scale. Furthermore, use of two-node size dependent axisymmetric shell element considerably reduces the amount of computations and analysis time in comparison with other methods. In the present paper, using the finite element method and modified couple stress theory, a new two-node size dependent axisymmetric shell element is introduced and mass and stiffness matrix are developed using axisymmetric shell element. The application of this axisymmetric shell element is outlined and the results are compared with those obtained by classical continuum theory and software. The correctness of the equations is demonstrated, and the results obtained by the modified couple stress theory in comparison with those obtained by the classical continuum theory are demonstrated. The results reveal that using the modified couple stress axisymmetric shell element, the rigidity of the nanoshell is greater than that in the classical continuum theory, which results in increase in natural frequencies. The size-dependent finite element formulation with axisymmetric shell element is very appropriate for precise solving of the vibration of nanotubes using modified couple stress theory.