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Variational approach for wave dispersion in anisotropic doubly-curved nanoshells based on a new nonlocal strain gradient higher order shell theory

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ABSTRACT

In this paper, a variational approach for the wave dispersion in anisotropic doubly-curved nanoshells is presented. To study the doubly-curved nanoshell as a continuum model, a new size-dependent higher-order shear deformation theory is introduced. In order to capture the small scale effects, nonlocal strain gradient elasticity theory has been implemented. The present model incorporates two scale coefficients to examine the wave characteristics much accurately. Based on Hamilton's principle, the governing equations of the doubly-curved nanoshells are obtained. These equations are solved via analytical approach. From the best knowledge of authors, it is the first time that present formulation is used to investigate the wave dispersion in anisotropic doubly-curved nanoshells. Also, it is the first time that small scale effects are considered in doubly-curved nanoshells made of anisotropic materials. Unlike the classical (scaling-free) model, the presented nonlocal strain gradient higher-order model shows a good calibration with the experimental frequencies and phase velocities. It is demonstrated that the material properties, nonlocal-strain gradient parameters and wave number have remarkable influences on wave frequencies and phase velocities. Presented results for wave dispersion can serve as benchmarks for future analysis of doubly-curved nanoshells.

1. Introduction

In recent years, the use of anisotropic materials as structural members has been increased considerably. This arises from the fact that although they have the advantages of light weight and high strength, their properties can also be tailored very efficiently by different methods such as variation of the fiber orientation. They can be found in variety of industries such as aircraft, missile, hydrospace, shipbuilding, auto industries, building construction, etc. [1]. The increased use of anisotropic shells in the design of various devices including their mechanical behavior in response to the conditions they are subjected to, have attracted the attention of many researchers in the past. Numerous studies on the various behaviors of shells have been provided in the open literature [2–4]. However, a reduced number of these works have as object of investigation, the wave dispersion behavior of micro/nano shells [5,6].

Shells are stiffer compared to plates. The strong point of the shells is their ability of combining membrane and bending action due to their curvature. Three different ways for studying shell structures can be introduced: the 3D Elasticity [7–9], Equivalent Single Layer (ESL) [10–13] and Layer Wise (LW) [14–17] theories. The theory proposed in present paper is based on a single layer model using a higher order shear deformation theory. Although up to now, several different models have been developed within a significant number of higher-order shear deformation theories [18–24], but here we present a new higher order model for studying nanoshells which may be a bench mark for some other researchers.

Nowadays, with the development of technology, a thorough understanding of the behavior of micro/nano structures is important, and many researchers have studied the properties and behavior of these structures. Experimental studies have demonstrated that the behaviors of materials in nanoscale are different compared to macro scale. Regarding the efficiency of micro/nano structures, numerous studies have been done on their mechanical responses [25–35]. Due to the superior properties of nanostructures, these materials have improved their performance in different fields in these days and several different nanostructures include nanoplates, nanobeams, nanodiscs, and nanoshells have been chosen for the subject of different researches [36–41]. An accurate understanding of the behavior of materials at the nanoscale is very important. For this purpose, appropriate models should be defined. As an important step for modeling nanoscale structures, the applicability of nonlocal elasticity theory with one distinct length scale

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parameter was examined by Eringen [42]. It was shown that the nonlocal elasticity theory can produce a softening-stiffness effect with increasing the nonlocal parameter. Mechanical buckling analysis of double-walled carbon nanotubes was investigated via nonlocal elasticity theory by Benguediab et al. [43]. Based on nonlocal elasticity theory large amplitude vibration analysis of nanoshells is studied by Rouhi et al. [44]. Mercan and Civalek [45] investigated the stability of the Silicon carbide nanotube (SiCNT) in the static buckling case with surface effect. Buckling behavior of SiCNTs was discussed using the continuum model via the Euler-Bernoulli beam theory for different boundary conditions in conjunctions with the surface effect and nonlocal elasticity theory. Sahmani and Aghdam [46] investigated size dependency in axial post buckling behavior of hybrid FGM exponential shear deformable nanoshells via nonlocal elasticity theory. Shahsavari and Janghorban [47] investigated the bending and shear responses for dynamic analysis of single layer graphene under moving load based on nonlocal elasticity. Also Shahsavari et al. [48] studied the dynamic characteristics of viscoelastic nanoplates under moving load resting on visco-Pasternak foundation and hygrothermal environment basis on nonlocal elasticity theory. With more detailed studies on nonlocal elasticity theory, the capability of this model for predicting the behaviors of all size-dependent mechanisms is doubtful. Several investigators have indicated a stiffness enhancement that is not included in nonlocal elasticity. It is reported that the nonlocal elasticity theory is unable to predict the stiffness-hardening effects by introducing the length scale parameter. Dou to this problem, Lim et al. [49] presented the nonlocal strain gradient elasticity theory. In the nonlocal strain gradient theory, the stress field accounts for not only the nonlocal stress field but also the strain gradients stress field. Nami and Janghorban [50] proposed a nonlocal elasticity and strain gradient theory for resonance behavior of functionally graded rectangular micro/nano plate. Li et al. [51] studied wave propagation in carbon nanotubes with surface effects based on nonlocal strain gradient theory. Applicability of nonlocal strain gradient theory for axial buckling analysis of nanotubes were studied by Mehralian et al. [52]. The governing equations and boundary conditions were derived using the minimum potential energy principle. The small length scale parameters were calibrated for the axial buckling problem of carbon nanotubes (CNTs) using molecular dynamics (MDs) simulations. In another work, two small length scale parameters was utilized to investigate the free vibration of nanotubes by Mehralian et al. [53]. A new size-dependent shell model formulation was developed using the first order shear deformation theory. Since the values of two small length scale parameters are still unknown, they were calibrated by the means of molecular dynamics simulations. Karami et al. [54] analyzed wave propagation in functionally graded nanoplates under in-plane magnetic field based on nonlocal strain gradient theory. Also, Karami et al. [55] investigated the effects of triaxial magnetic field in anisotropic materials on basis of mentioned theory but still there isn't any research on wave dispersion in anisotropic doubly-curved nanoshell via nonlocal strain gradient theory. Zeighampour et al. [56] proposed a nonlocal strain gradient theory to investigate the wave propagation behavior of fluid-conveying double-walled carbon nanotube. Also, Zeighampour et al. [57] presented wave propagation in viscoelastic single walled carbon nanotubes by accounting for the simultaneous effects of the nonlocal constant and the material length scale parameter. In another work, Zeighampour et al. [58] presented wave propagation analysis of viscoelastic single walled carbon nanotubes via a nonlocal strain gradient thin shell model. Their results shown that viscoelastic single walled carbon nanotube rigidity is higher in the strain gradient theory and lower in the nonlocal theory in comparison to that in the classical theory. Shahsavari et al. [59] investigated the shear buckling of single layer graphene sheets in hygrothermal environment resting on elastic foundation based on different nonlocal strain gradient theories. Size dependent analysis of wave propagation in functionally graded composite cylindrical microshell reinforced by carbon nanotube were studied by Zeighampour and Beni [60]. The FG-CNTRC cylindrical microshell was modeled using shear deformable shell theory as well as nonlocal strain gradient theory.

It is evident from the above literature that no studies have been reported to address the issues related to the wave dispersion analysis of doubly-curved structures made of anisotropic materials using Nonlocal Strain Gradient Theory (NSGT). In present article, NSGT which contains both nonlocal and length scale parameter is employed for more accurate description of size effects to examine the dispersion behavior of size-dependent anisotropic doubly-curved nanoshells. One of the objective of this article is to show the necessity of the higher-order models for the analysis of the wave dispersion behavior of the doubly-curved nanostructure by comparing the responses with the available numerical results. In order to do so, a general mathematical model of the doubly-curved nanoshell has been developed using a new higher order shear deformation theory and solved using an analytical approach. The desired responses are obtained using the customized homemade computer code in MATLAB environment. It will be presented that the developed nonlocal strain gradient higher-order model depicts different behaviors of flexural frequencies and phase velocities, and shows a good agreement with the experimental frequencies and phase velocities. Finally, the study has been extended to show the applicability of the proposed higher-order model for the evaluation of wave dispersion behavior of doubly-curved nanoshell. The effect of the material properties, nonlocal strain gradient parameters and wave number on the frequency responses as well as phase velocity variations are also computed and discussed in detailed.

2. Anisotropic materials

For almost all types of elastic materials such as isotropic and anisotropic materials, Hook's law usually represents the material behavior and relates the unknown stresses and strains. The general equation for Hooke's law is,

$$\sigma = C\varepsilon \tag{1}$$

in which σ and ε are stress and strain components, respectively and C is the elastic constant that is different in various structures. As a consequence, the above stress-strain relations are governed by,

$$\begin{Bmatrix} \sigma_{\alpha\alpha} \\ \sigma_{\beta\beta} \\ \sigma_{zz} \\ \tau_{\alpha z} \\ \tau_{\beta z} \\ \tau_{\alpha\beta} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{\alpha\alpha} \\ \varepsilon_{\beta\beta} \\ \varepsilon_{zz} \\ \gamma_{\varepsilon z} \\ \gamma_{\beta z} \\ \gamma_{\alpha\beta} \end{Bmatrix} \tag{2}$$

One the main topics in the study of mechanical structures is the study of anisotropic materials which has attracted the attention of researchers today. Although numerous studies are available for the analysis of micro/nano structures with isotropic material properties, however, a few studies on anisotropic materials have been performed due to the structural complexity of anisotropic materials in comparison with isotropic materials in nanoscale. According to the superbly anisotropic material properties, the analysis of anisotropic micro/nano structures may be required for future industrial usages. In the below, four examples of anisotropic materials which are used in this article are presented.

2.1. Hexagonal materials

In materials with hexagonal crystallinity the crystal is conventionally described by a right rhombus prism unit cell with two equal axes. The hexagonal crystal family consists of the 12 point groups such that at least one of their space groups has the hexagonal lattice as underlying lattice, and is the union of the hexagonal crystal system and the trigonal crystal system.

One of the materials with hexagonal system is beryllium crystal. It