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Review

A review on the mechanics of nanostructures

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ABSTRACT

Understanding the mechanical behaviour of nanostructures is of great importance due to their applications in nanodevices such as in nanomechanical resonators, nanoscale mass sensors, electromechanical nanoactuators and nanogenerators. Due to the difficulties of performing accurate experimental measurements at nanoscales and the high computational costs associated with the molecular dynamics simulations, the continuum modelling of nanostructures has attracted a considerable amount of attention. Since size influences have a crucial role in the mechanics of structures at nanoscale levels, classical continuum-based theories have been modified to incorporate these effects. Among various modified continuum-based theories, the nonlocal elasticity and the nonlocal strain gradient elasticity have been employed to estimate the mechanical behaviour of nanostructures. In this review paper, first these two modified elasticity theories are briefly explained. Then, the nonlocal motion equations for different nanostructures including nanorods, nanorings, nanobeams, nanoplates and nanoshells are derived. Several papers which reported on the size-dependent mechanical behaviour of nanostructures using modified continuum models are reviewed. Furthermore, important results reported on the vibration, bending and buckling of nanostructures as well as the results of size-dependent wave propagation analyses are discussed.

1. Introduction

Nanoscale structures including nanoscale rods (Xu et al., 2004), rings (Cui, Gu, Xu & Shi, 2006), beams (Iijima & Ichihashi, 1993, Barretta, Čanađija, Luciano & de Sciarra, 2018, Barretta & Marotti de Sciarra, 2018, Hadi, Nejad & Hosseini, 2018, She, Ren, Yuan & Xiao, 2018, Khaniki, 2018), plates (Geim & Novoselov, 2010, Jalaei, Arani & Tourang, 2018), and shells (Loo et al., 2005, Faleh, Ahmed & Fenjan, 2018) have been utilised as the fundamental structural parts of many nanoelectromechanical systems (NEMS). Nanomechanical resonators (Eichler et al., 2011, Farokhi, Païdoussis & Misra, 2018), nanoscale mass sensors (Zhao, Gan & Zhuang, 2002), electromechanical nanoactuators (Fennimore et al., 2003), and nanoenergy harvesters (Briscoe & Dunn, 2015) are salient examples of these NEMS-based devices. These valuable nanoscale devices have broad applications in different areas of nanotechnology such as nanoelectronics, nanomachines and nanomedicine. To achieve a better performance for the nanodevice, a better understanding of the mechanical characteristics of nanostructures as these ultrasmall structures are usually subject to mechanical loads, pressure or stresses. In addition, in nanodevices such as nanoscale generators (Chu et al., 2016, Kwon, Sharma & Ahn, 2013), the mechanical energy is converted into electricity, hence an analysis on the mechanical behaviour is essential.

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Since performing an accurate experimental measurement at nanoscale levels is challenging, continuum-based modelling and molecular dynamics (MD) simulations of nanostructures have attracted a considerable amount of attention. Using continuum-based models and the results of MD simulations, the number of required experimental measurements can be reduced. Compared to MD simulations, the continuum modelling of nanostructures is less computationally expensive. Particularly, performing MD simulations on a nanostructure with a large number of molecules requires a high computational effort. Using continuum models, the mechanical characteristics can be formulated and estimated. In this way, the computational costs of MD simulations can be reduced by eliminating unnecessary simulations. In addition, the continuum-based modelling of nanostructures can help us to better understand the results of experimental measurements or molecular dynamics.

Scale effects have a crucial role to play in the mechanics of nanostructures, as opposed in macrostructures (Ghayesh, Païdoussis & Amabili, 2013, Ghayesh & Amabili, 2012, Ghayesh & Amabili, 2013, Ghayesh, Amabili & Paidoussis, 2012, Ghayesh, 2009, Ghayesh, 2011, Gholipour, Ghayesh, Zander & Mahajan, 2018). Thus, traditional continuum-based theories, which are scale-free, have been modified in order to capture size effects. Various size-dependent theories for examining the mechanical characteristics of nanostructures have been introduced in recent years. Since the mechanical behaviour of structures at microscale levels (Ghayesh & Farokhi, 2015, Gholipour, Farokhi & Ghayesh, 2015, Ghayesh, Amabili & Farokhi, 2013, Ghayesh, Farokhi & Amabili, 2013, Ghayesh, Farokhi & Amabili, 2014, Ghayesh & Farokhi, 2015, Farokhi & Ghayesh, 2015, Farokhi & Ghayesh, 2015, Ghayesh, Farokhi & Gholipour, 2017, Farokhi & Ghayesh, 2018, Ghayesh, Farokhi, Gholipour & Tavallaeinejad, 2018, Dehrouyeh-Semnani, Nikkhah-Bahrami & Yazdi, 2017, Ghayesh & Farokhi, 2017) is different from that observed at nanoscale levels, the modified continuum-based theories of microstructures are different from those of nanostructures (Lei et al., 2016). In general, the structural stiffness hardening is observed at microscale levels whereas the mechanics of nanostructures is usually governed by the stiffness softening. Therefore, size-dependent models including the couple stress (Farokhi, Ghayesh & Amabili, 2013, Ghayesh, Farokhi & Alici, 2015, Farokhi, Ghayesh, Gholipour & Hussain, 2017, Ghayesh & Farokhi, 2017, Farokhi & Ghayesh, 2018, Farokhi & Ghayesh, 2018, Ghayesh, 2018, Ghayesh & Farokhi, 2018, Ghayesh, Farokhi & Alici, 2016, Ghayesh, Farokhi & Amabili, 2013, Ghayesh, Farokhi & Gholipour, 2017) and strain gradient elasticities (Ghayesh, Amabili & Farokhi, 2013, Akgöz & Civalek, 2011, Akgöz & Civalek, 2013) are often used to analyse the mechanical behaviour of microstructures including microbeams, microbars and microplates while the nonlocal elasticity theory (Pradhan & Phadikar, 2009, Reddy, 2007, Farajpour, Shahidi & Farajpour, 2018, Asemi & Farajpour, 2014) is applied to nanoscale structures. However, to have a more general size-dependent continuum-based model capable of predicting size effects at different small scales, a combination of these modified elasticity theories (Lim, Zhang & Reddy, 2015) can be employed.

This review article is organised as follows: In Section 2, concise information is given about different size-dependent elasticity theories utilised for investigating the mechanical characteristics of structures at nanoscale levels including the pure nonlocal and nonlocal strain gradient elasticities. In Section 3, first the size-dependent motion equations of various types of nanoscale structures such as nanoscale rods, rings, beams, plates and shells are developed via the nonlocal elasticity. Then, studies on the size-dependent modelling of the mechanical behaviour of these structures are reviewed; particular attention is paid to the size-dependent bending, buckling and vibration of nanoscale structures as well as size-dependent wave propagations in these small-scale structures. Finally, Section 4 concludes on the size-dependent continuum theories of nanostructures, and the most important findings to date are highlighted.

2. Size-dependent continuum mechanics

In this section, size-dependent (Ghayesh, Farokhi & Hussain, 2016, Farokhi & Ghayesh, 2016, Ghayesh & Amabili, 2014, Ghayesh, 2018, Ghayesh, 2018, Ghayesh, Farokhi, Gholipour & Tavallaeinejad, 2017, Ghayesh, Farokhi, Gholipour & Hussain, 2017, Farokhi, Ghayesh, Gholipour & Tavallaeinejad, 2017, Farokhi, Ghayesh & Gholipour, 2017, Ghayesh, Farokhi & Farajpour, 2018) elasticity theories including the nonlocal elasticity and the nonlocal strain gradient elasticity, which are commonly applied to nanoscale structures, are reviewed. Firstly, the basic concept of the nonlocal elasticity is clarified, and then both the integral and differential nonlocal constitutive relations are discussed. Finally, the theory of the nonlocal strain gradient elasticity is introduced.

2.1. Nonlocal elasticity theory

The nonlocal elasticity was introduced by Eringen (Eringen & Edelen, 1972, Eringen & Nonlocal, 2002) almost two decades before the invention of carbon nanotubes (CNTs). However, this valuable theory did not attract much attention until the synthesis of nanostructures such as CNTs and graphene sheets (GSs) emerged. Peddieson et al. (Peddieson, Buchanan & McNitt, 2003) first suggested that the theory can be used to analyse the size-dependent mechanical response of nanostructures. In the classical elasticity theory, which is not able to predict size effects, the stress at a spot is only dependent on the strain at that spot. By contrast, in the nonlocal elasticity, strains at all spots affect the stress at one arbitrary spot as shown in Fig. 1. This basic assumption allows this theory to capture intermolecular interactions, leading to a size-dependent theory of elasticity. Ignoring body forces, the nonlocal integral constitutive relation is given by

$$\sigma_{ij}^{nl} = \int\int_{V}\int \varphi\left(\left|\mathbf{X}-\mathbf{X}'\right|, \eta\right)\sigma_{ij}^{l} dV, \tag{1}$$