Physica E 66 (2015) 283–292

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Wave propagation analysis in nonlinear curved single-walled carbon nanotubes based on nonlocal elasticity theory

Bo Wang [a,b], Zichen Deng [a,*], Huajiang Ouyang [b], Jiaxi Zhou [c]

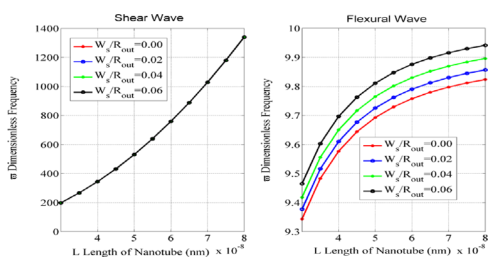
[a] Department of Engineering Mechanics, Northwestern Polytechnical University, Xi'an 710072, China
[b] School of Engineering, University of Liverpool, Liverpool L69 3GH, UK
[c] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China

HIGHLIGHTS

- A more accurate model for nonlinear curved single-walled carbon nanotubes (SWCNTs) via the nonlocal elasticity theory has been constructed.
- The linearization method has been developed to study the wave characteristic of nonlinear curved SWCNTs.
- The dispersion curves in the manuscript reveals the influence of the nonlocal parameter on wave characteristics.
- As the value of nonlinearity increases, the shear frequency drops, while the flexural frequency has an opposite tendency.
- The temperature change and magnetic flux make the nanotubes stiffer.

GRAPHICAL ABSTRACT

Wave analysis has been used to investigate the wave characteristic of single-walled carbon nanotube (SWCNT) with geometrical nonlinearity and imperfection. The influences of the geometrical nonlinearity and imperfection on the vibration frequencies.



ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
20 September 2014
Accepted 23 September 2014
Available online 2 October 2014

Keywords:
Single-walled carbon nanotubes
Nonlocal timoshenko beam theory
Geometrically nonlinearity
Geometrical imperfection
Wave propagation
Temperature change
Magnetic field

ABSTRACT

Theoretical predictions are presented for wave propagation in nonlinear curved single-walled carbon nanotubes (SWCNTs). Based on the nonlocal theory of elasticity, the computational model is established, combined with the effects of geometrical nonlinearity and imperfection. In order to use the wave analysis method on this topic, a linearization method is employed. Thus, the analytical expresses of the shear frequency and flexural frequency are obtained. The effects of the geometrical nonlinearity, the initial geometrical imperfection, temperature change and magnetic field on the flexural and shear wave frequencies are investigated. Numerical results indicate that the contribution of the higher-order small scale effect on the shear deformation and the rotary inertia can lead to a reduction in the frequencies compared with results reported in the published literature. The theoretical model derived in this study should be useful for characterizing the mechanical properties of carbon nanotubes and applications of nano-devices.

1. Introduction

Due to their excellent mechanical, physical, chemical, electrical and vibration properties, carbon nanotubes (CNTs) have potential applications [1] in various engineering areas. For example, CNTs-reinforced composites can offer stiffness and strength at an order

* Corresponding author.
E-mail addresses: bobowang0406@gamil.com (B. Wang), dweifan@nwpu.edu.cn (Z. Deng).

http://dx.doi.org/10.1016/j.physe.2014.09.015
1386-9477/

of magnitude higher than conventional materials, and the high frequency of CNTs can be exploited to design Nano-Electro-Mechanical Systems (NEMS). Numerous studies in the open literature [2] have described a variety of CNTs-based sensors and devices, including mass sensors, charge detectors, and nano-oscillators.

To design novel nano-devices, it is essential to have rigorous understanding of their physical properties, for example, Young's modulus and shear modulus. Recently, the continuum mechanics models [3], such as Euler-Bernoulli, Timoshenko, Reddy, Levinson beams, plates, and shells, play an important role in the study of CNTs, as compared with experiments and atomistic models. Especially the nonlocal theory of elasticity, initiated by Eringen [4,5] and Edelen [6], which takes the small scale effect into account, has been widely used to determine the effective elastic modulus of CNTs in an indirect way and explore the dynamic behavior of CNTs. Different from the conventional theory of elasticity, the nonlocal theory of elasticity assumes that the stress at a point in the continuous domain is dependent not only on the strain at that point but also on the strains of all points in the domain. Thus, the internal length scale, for example the inter-atomic bond, has been introduced into the nonlocal constitutive equations.

As mentioned in [7], the wave propagation problem is so important that it has attracted worldwide attention [8–12] in many areas of science and engineering. Lim and Yang [7] studied wave propagation in CNTs based on the nonlocal elastic stress field theory and Timoshenko beam theory, and obtained new dispersion and spectrum relations. On the basis of the nonlocal elastic cylindrical shell theory, Hu et al. [8] studied the transverse and torsional waves in SWCNTs and double-walled carbon nanotubes (DWCNTs); by comparing the wave dispersion predicted by their model with the molecular dynamics simulations in terahertz region, their results indicated that the nonlocal model could provide a better predication of the dispersion relationships. Considering the CNTs and nanoplates (graphene) under magnetic field, they showed exciting potential applications in spintronics, microwave absorbing and other NEMS devices.

In recent years, there are many investigations [13–16] on electromagnetic characteristics of CNTs and the magnetic properties of CNTs. Wang et al. [13] discussed the influence of longitudinal magnetic field on wave propagation in CNTs embedded in elastic matrix, and their results revealed that in some frequency regions, as the longitudinal magnetic field increased, the wave velocity increased. Based on the nonlocal Euler-Bernoulli beam theory, ultrasonic or terahertz wave dispersion characteristics of SWCNTs under the longitudinal magnetic field were investigated by Narendar et al. [14]; and they found that the band gap in the flexural wave was independent of the longitudinal magnetic field. In addition to magnetic field, CNTs-based devices may work in complex physical environments [17]. Some physical properties of CNTs can be greatly improved if they work in temperature field [18–21], for example, the thermal conductivity is twice as large as diamond, and the electric-current carrying capacity is thousand times greater than copper wire. Wave propagation of CNTs in a thermal environment was investigated by Benzair et al. [22] on the basis of nonlocal Timoshenko beam theory; they discussed the effect of temperature change on the properties of transverse vibration of CNTs. Amirian et al. [23] analyzed the thermal-elastic vibration of short SWCNTs based on nonlocal Timoshenko beam model, and their results showed that at all temperatures the natural frequencies by nonlocal model were always smaller than those predicted by the local model.

In nature, the deformations of CNTs are nonlinear [24]. However, all the studies mentioned above are limited to linear regime. As indicated by Postma et al. [25], a strongly nonlinear response combined with a high thermo-mechanical noise level would limit the usefulness of nano-mechanical resonators. Only when the nonlinearities in geometry and physics are taken into account [26–35], the more precise static and dynamic properties of CNTs can be obtained and then the CNTs can have wider applications. For example, combining the great importance of signal mixing with the advantages of the nonlinear nanomechanical systems, Erbe et al. [36] found that the insensitivity of NEMS devices to the extremes of temperature and radiation was very promising, especially once the high speed of operation became available. The intrinsic nonlinearity was introduced into NEMS through a geometric design in [24]. It is noted that Khorasany and Hutton [37] studied the effect of temperature and geometrical nonlinearity on the amplitude and phase velocity characteristics of SWCNTs based on Euler–Bernoulli beam model. However, in most past papers, the effect of a certain degree of curvature or waviness along the nanotube length produced during manufacturing processes, on the mechanical properties and dynamical behavior of CNTs has been neglected. This effect was found to exist by transmission electron microscopes [38]. In very recent years, more and more researchers [39,40] realize the importance of surface waviness and then the dynamical behavior of wavy CNTs has been studied [41–43].

The aim of this article is to study wave propagation in nonlinear wavy SWCNTs. Based on nonlocal Timoshenko beam theory, a more sophisticated theoretical model is established. By using the linearization method, reported in published works [37,44], the natural frequencies are obtained. The analytical model is derived, and the effectiveness of the model, the effects of the small scale, the nonlinearity, the temperature change and the magnetic field on the shear frequencies and flexural frequencies are analyzed.

The structure of this article is organized as follows. In Section 2, detailed formulations of the problem are introduced. Wave analysis is carried out to study the dispersion relations in Section 3. Finally, numerical results are given in Section 4 to validate the proposed computational model, and the influences of mechanical parameters, such as the nonlocal parameter, the values of waviness, and the nonlinearity, are discussed. In Section 5, the concluding remarks are given.

2. Formulation of the problem

2.1. Derivation of the equation of motion

The displacement fields of a beam at any point can be given as [41]

$$\begin{cases} U_1(x,t) = u(x,t) + z\varphi(x,t) \\ U_2(x,t) = w(x,t) \end{cases} \tag{1}$$

where $u(x,t)$ and $w(x,t)$ are the axial and transverse displacements of the neutral axis, and $\varphi(x,t)$ denotes the rotation of the cross section.

Considering the effects of the bending-induced deformation and the process-induced waviness along the length of CNTs, the non-zero stains of the Timoshenko beam can be expressed as [41]

$$\begin{Bmatrix} \boldsymbol{\varepsilon}_{\mathbf{xx}} \\ \gamma_{xz} \end{Bmatrix} = \begin{Bmatrix} \partial u/\partial x \\ \partial w/\partial x \end{Bmatrix} + \begin{Bmatrix} z\partial\varphi/\partial x \\ \varphi \end{Bmatrix} + \begin{Bmatrix} 1/2(\partial w/\partial x)^2 + \partial w/\partial x\, \partial w_0/\partial x \\ 0 \end{Bmatrix} \tag{2}$$

where $\boldsymbol{\varepsilon}_{\mathbf{xx}}$ is the normal strain in the x direction, and $\boldsymbol{\gamma}_{xz}$ is the transverse shear strain. w_0 is a small rise function, which is used to describe the initial geometrical imperfection.