International Journal of Mechanical Sciences 87 (2014) 179–199

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Longitudinally varying magnetic field influenced transverse vibration of embedded double-walled carbon nanotubes

Keivan Kiani *

Department of Civil Engineering, K.N. Toosi University of Technology, P.O. Box 15875-4416, Tehran, Iran

ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form
2 April 2014
Accepted 21 April 2014
Available online 29 April 2014

Keywords:
Double-walled carbon nanotube (DWCNT)
Free transverse vibration
Longitudinally varying magnetic field
Nonlocal beam theories
Reproducing kernel particle method (RKPM)

ABSTRACT

Using nonlocal Rayleigh, Timoshenko, and higher-order beam theories, the free dynamic deflection of elastically supported double-walled carbon nanotubes (DWCNTs) subjected to a longitudinally varying magnetic field (LVMF) is examined. By employing reproducing kernel particle method (RKPM), the equations of motion of the magnetically affected DWCNT (MADWCNT) for each model are reduced to a set of algebraic equations. For four common boundary conditions, namely fully simple, fully clamped, simple-clamped, cantilevered supports, the dominant frequencies of the nanostructure are calculated. In particular cases, the predicted results by the RKPM are compared with those of the exact solution. Additionally, the convergence checks of the proposed numerical models are performed. The effects of the innermost radius, slenderness ratio, small-scale parameter, maximum strength of the LVMF, transverse and rotational stiffness of the surrounding medium on the fundamental frequency of the MADWCNT are addressed. The capabilities of the proposed models in predicting the characteristics of free vibration are also discussed. Further, the limitations of the local analysis as well as the classical beam theory in capturing the lateral vibrations of the MADWCNTs are revealed.

1. Introduction

Assemblage of nanoscale materials over macroscopic dimensions as well as progress of novel nano-electro-mechanical systems (NEMS) hold great promise for a diverse range of applications in nanotechnology. However, there has been a great challenge to find an efficient way to control both assembling of such materials and their dynamic response at the nanoscale level. Carbon nanotubes (CNTs) are considered as one of the most promising materials in nanotechnology. Such an enormous confidence in their usage is chiefly indebted to their excellent electrical, mechanical, chemical, and physical properties [1–5]. One practical way to reach the above-mentioned goals of interest would be applications of appropriate electrical and magnetic fields.

The experimentally observed data have revealed that when the CNTs-matrix is acted upon by a magnetic field, CNTs could be aligned along the direction of the applied magnetic field [6–8]. Additionally, further studies show that the electro-thermo-mechanical properties of CNTs and their composites are generally enhanced by magnetic field processing [9–13]. Thereby, realization of vibration behavior of magnetically affected CNTs-composites would be of great significance from two standpoints: optimal design and vibration control. A class of CNTs family which is of concern in the present work is double-walled carbon nanotubes (DWCNTs). Such nanostructures are composed of two coaxial single-walled carbon nanotubes (SWCNTs), one nested in another at the vicinity of each other. The morphology and properties of DWCNTs are mostly identical to those of SWCNTs, however, their resistance to chemicals is highly enhanced. This is mainly related to this fact that in SWCNTs, covalent functionalization will break some C-C bonds causing some damages within the nanostructure. Thereby, both electrical and mechanical properties would be modified. In the case of DWCNTs, only the properties of the outer wall are modified. Such an important advantage of DWCNTs provides them as a more efficient functionalized nanostructure in comparison to SWCNTs, particularly when adding new properties to the nanostructure is of concern. In this work, only transverse vibration of a system of DWCNTs-matrix is of concern. Therefore, the magnetically affected DWCNTs (MADWCNTs) can be reasonably simulated via well-known beam theories and their interactions with its surrounding matrix are taken into account by continuous transverse and rotational springs. Further, we study the transverse vibration of an individual DWCNT embedded in an elastic matrix subjected to an arbitrarily longitudinal magnetic field. For a group of DWCNTs embedded in matrix (i.e., an ensemble of DWCNTs), more precise interactions between them

* Tel.: +98 21 88779473; fax: +98 21 88779476
E-mail addresses: k_kiani@kntu.ac.ir, keivankiani@yahoo.com

http://dx.doi.org/10.1016/j.ijmecsci.2014.04.018
0020-7403/

and its surrounding medium because of the composite action as well as the interactions between individual DWCNTs due to the van der Waals (vdW) interactional forces should be considered. Herein, we focus on the free dynamic behavior of an elastically embedded DWCNT with elastic supports in order to cover a wide range of mechanical properties of the matrix as well as boundary conditions.

To date, free and forced vibrations of both SWCNTs and DWCNTs due to a set of numerous effects have been of concern of researchers of various disciplines. Their free vibrations and elastic wave propagation within them in the absence of the magnetic field [14–22] as well as in its presence [23–28] have been extensively investigated. Most of these studies were carried out in the context of the nonlocal continuum theory. Forced vibrations of such nanostructures due to an inside fluid flow [29–32] and a moving nanoparticle [33–39] have been widely addressed, however, the author believes that further research works should be performed for more realistic modeling of such effects. Additionally, magneto-elasto-dynamic fields within nanowires due to a longitudinal unsteady magnetic field have been examined [40,41]. Based on the literature, the undertaken works regarding the influence of the magnetic field on the vibration of DWCNTs were restricted to the case in which the strength of the magnetic field was uniform along the nanostructure [23–27]. To study the DWCNT subjected to a more general distribution of the longitudinal magnetic field, the governing equations should be reconstructed from the basic equations of elasticity of beams and those of Maxwell and Lorentz. This work has been devoted to answer this question that how a longitudinally varying magnetic field could affect vibration behavior of DWCNTs with various boundary conditions and different levels of the slenderness ratio. For this purpose, the equations of motion of the MADWCNT are gained on the basis of the Rayleigh, Timoshenko, and higher-order beam theories as well as Maxwell's equations. Seeking an analytical solution to the governing equations is a problematic task; therefore, an efficient meshless methodology, namely reproducing kernel particle method (RKPM), is implemented. RKPM was developed by Liu et al. [42,43], and so far, it has been successfully applied to many dynamical problems in engineering and physics sciences [20,28,44–48]. The obtained results by this method have been reasonably in good agreement with those of other reliable works in most of the cases.

This paper is organized as follows: in Section 2, the description of the problem under study plus to the made assumptions are given. In Section 3, the exerted forces on an individual DWCNT due to the longitudinally varying magnetic field (LVMF) are evaluated. In Sections 4–6, the nonlocal governing equations for the problem at hand are obtained via nonlocal Rayleigh beam theory (NRBT), nonlocal Timoshenko beam theory (NTBT), and nonlocal higher-order beam theory (NHOBT), respectively. Additionally, the numerical solutions based on the RKPM are presented for the frequency analysis of the problem based on the proposed models. The numerical studies including convergence check, verification of the obtained results, and the roles of influential parameters on the frequencies of the MADWCNTs are provided in Section 7. Finally, the crucially obtained results will be briefly expressed in Section 8.

2. Definition of the nanomechanical problem

Consider a DWCNT which is embedded in an elastic matrix as shown in Fig. 1(a). The DWCNT is subjected to a LVMF of strength $H_x(x)$ which is applied just at the vicinity of the outer surfaces of both the innermost and outermost tubes. For continuum-based modeling of the MADWCNT, each tube is substituted by an equivalent continuum structure (ECS) (see Fig. 1(b)). An ECS is an isotropic hollow cylindrical solid whose most of its longitudinal, torsional, and flexural frequencies, particularly the dominant ones, are the same as those of the origin tube. By considering an ECS of mean radius and length identical to those of the tube, Gupta and Batra [49] as well as Gupta et al. [50] predicted the thickness and elastic properties of the ECS by comparing its dominant frequencies with those of molecular dynamics approach. In most of the cases, the obtained results displayed that an ECS with the wall's thickness t_b=0.34 nm, elastic modulus E_b=1 TPa, and Poisson's ratio $\nu_b = 0.3$ would be a reasonably good replacement for the original CNT under consideration. For continuum-based modeling of the problem, the cross-sectional area, moment inertia, density, mean radius, and shear elasticity modulus of the ith tube are denoted by A_{b_i}, I_{b_i}, ρ_{b_i}, r_{m_i}, and $G_{b_i}; i = 1,2$, respectively. The parameters with the subscripts 1 and 2 in order are associated with the innermost and outermost tubes. During the transverse deformation of the DWCNT, the atoms of the innermost tube and those of the outermost tube are interacted with each other by the van der Waals (vdW) forces which are commonly evaluated via Lennard Jones potential function. Such interactional forces can be approximately modeled by continuous lateral springs of constants $C_v/2$, connecting the innermost tube to the outermost tube from the bottom and the top. The magnitude of C_v could be calculated as given in detailed in Ref. [35]. The confinement effect due to the surrounding elastic matrix is taken into account for the proposed models by continuously attached lateral and torsional springs with constants, K_t and K_r, respectively. In order to examine the problem for a wide range of boundary conditions, both ends of the ith tube have been attached to elastic transverse and rotational springs of constants $K_{z_i}(x_k)$ and $K_{y_i}(x_k)$; $k = 1,2$, respectively, where $x_1 = 0$ and $x_2 = l_b$.

In the following parts, the exerted forces on the innermost and outermost tubes of the MADWCNT are assessed by using Maxwell's equations. The equations of motion of MADWCNTs acted upon by a LVMF based on the NRBT, NTBT, and NHOBT are then obtained. Subsequently, application of the RKPM to the resulted governing equations as well as the frequency analyses of the proposed models will be explained in some detail.

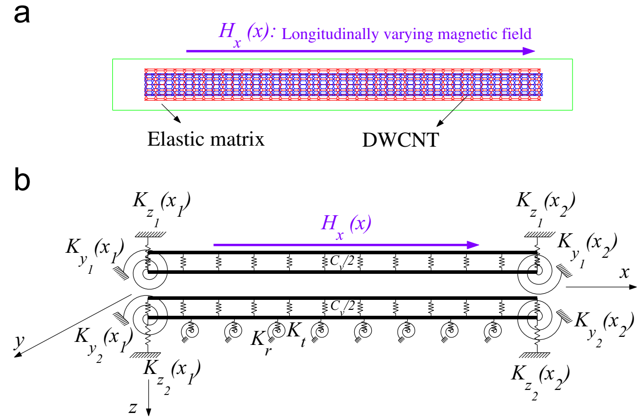

Fig. 1. (a) A DWCNT embedded in an elastic matrix acted upon by a LVMF. (b) The continuum-based configuration of the embedded DWCNT with elastic supports subjected to a LVMF.

3. Induced forces on a continuum-based DWCNT due to a LVMF

According to Maxwell's equations [51–54], the B–D–E–H–J relations are given by the following four equations:

$$\nabla \times \mathbf{H} = \dot{\mathbf{D}} + \mathbf{J},$$