Computers and Mathematics with Applications ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

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

Nonlocal free dynamic analysis of periodic arrays of single-walled carbon nanotubes in the presence of longitudinal thermal and magnetic fields

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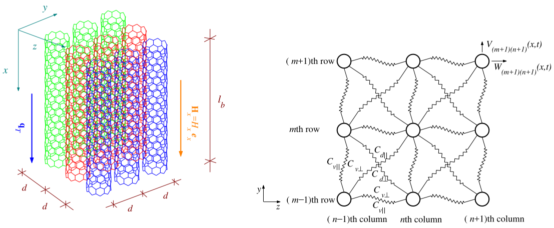
GRAPHICAL ABSTRACT



(a) (b)

Summary

Dynamic behavior of vertically aligned jungles of SWCNTs acted upon by both longitudinal magnetic and thermal fields is of high concern. Using higher-order beam theory, nonlocal discrete and continuous models are developed. The capabilities of these newly developed models in capturing fundamental frequency of the nanosystem as well as the roles of influential factors on this crucial parameter are addressed.

ARTICLE INFO

Article history:
Received 7 July 2017
Received in revised form 1 December 2017
Accepted 21 February 2018
Available online xxxx

Keywords:
Vertically aligned jungles of SWCNTs
Longitudinal magnetic field
Thermal field
Nonlocal elasticity theory
Higher-order beam model
Nonlocal continuous modeling

ABSTRACT

This paper deals with transverse vibrations of three-dimensional vertically aligned periodic arrays of single-walled carbon nanotubes acted upon by both longitudinal magnetic and thermal fields. For this purpose, a nonlocal higher-order beam theory is employed for modeling of the nanosystem. Accounting for the intertube van der Waals forces, a discrete-based model as well as a continuous-based model is established. For various geometries of the nanosystem and under various applied thermal and magnetic fields, the results of the continuous model are successfully checked with those of the discrete model. Through a comprehensive parametric study, the effects of the nanotube's radius, slenderness ratio, nonlocality, ensemble's population, temperature change, and strength of magnetic field on fundamental frequencies of the nanosystem are addressed and displayed.

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https://doi.org/10.1016/j.camwa.2018.02.033
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1. Introduction

From practical application viewpoint, it is extremely enviable to manufacture carbon nanotubes (CNTs) in large scales. This has brought about a new class of carbon nanotube material, called vertically aligned carbon nanotube jungles. Up to the type of their constitutive CNTs (i.e., single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs)), these are classified into two major groups: vertically aligned jungles of SWCNTs (VAJSWCNTs) and vertically aligned multi-walled carbon nanotubes (VAJMWCNTs). The VAJSWCNTs are commonly composed of a dense packing of individual SWCNTs with densities in the range of 10^8 tubes/cm^2–10^{13} tubes/cm^2. The VAJSWCNTs can be produced through a variety of synthesis methodologies, including electric arc discharge [1], chemical vapor deposition [2,3], laser ablation [4], and electrophoretic deposition [5].

A vast variety of applications could be found for VAJSWCNTs that are grown on various substrates (i.e., smooth metals or rounded carbon fibers). For example, those synthesized on planar surfaces, would have wide-ranging applications in areas such as the electrical interconnects [6–8], energy dissipation devices [9], thermal interface materials [10,11] and nano-/micro- electro-mechanical systems (NEMS and MEMS) [12–14]. Furthermore, those grown on rounded fibers can be exploited for enhancing the fiber–matrix interfaces in composite materials [15–17] or sensing flow (speed and pressure) [18–20]. The VAJSWCNTs reinforced with matrix composites form anisotropic conductive materials [21], whereas those developed on patterned substrates have potential applications in triode-type field emitters [22,23]. Owing to their large surface area and high thermal conductivity, they could quickly transfer heat to environs. This property provides them as important materials for construction of solar cells [24]. With regard to the interior and interstitial surfaces of SWCNTs owning strapping binding energy for adsorbing hydrogen molecules, VAJSWCNTs could be utilized as hydrogen storages [25]. Further, due to higher electrical conductivity and larger surface area of VAJSWCNTs with respect to entangled SWCNTs, they have been proposed as an ideal material for sensing pH [26], glucose [27–29] or even DNA [30,31].

Recent investigations on CNT-based composite materials reveal this truth that their mechanical behavior would be improved by application of the magnetic field [32,33]. Application of magnetic field is also known as an efficient way for aligning CNTs [34–36]. With regard to the aforementioned applications, magneto-thermo-mechanical analyses of vertically aligned CNTs arrays are highly of interest. These explorations could be considered as a primary investigation on magneto-thermo-mechanical analysis of composites with aligned CNTs. For this purpose, this study concerns examining vibrations of VAJSWCNTs in both thermal and magnetic fields. Actually, we are interested in realizing the crucial factors influence on natural flexural and shear frequencies of magnetically–thermally influenced VAJSWCNTs. The works on other mechanical aspects of such tiny nanosystems, including small and large static deformations, buckling, postbuckling, and large dynamical deflections, could be considered as hot topics for future works. It is also expected that this research work could give a solid step for upcoming studies on mechanical analysis of vertically aligned MWCNTs under multi-physical fields, which is of high concern for both applied mechanics community and nanotechnology.

In view of the fact that transverse vibration of CNTs is usually the most crucial one among various dynamical scenarios, appropriate beam theories could be employed for predicting such free or forced vibrations. For continuum-based modeling of vibrations of CNTs, the problem cannot be studied in the context of the classical elasticity theory (CET). It is chiefly related to this fact that this theory cannot explain the effect of vibrations of one atom on the vibrations of its neighbor atoms. To conquer this deficiency of the CET, Eringen [37–39] proposed nonlocal elasticity theory (NET). Based on this advanced theory of continuum mechanics, the true stress fields (i.e., nonlocal stresses) at a point are also influenced by the stresses of adjacent points. In the exact version of this theory, the nonlocal stress is defined by an integral of multiply of a kernel function by the local stress over the whole spatial domain of the continuum. The kernel function is an attenuating function with finite support domain (several of these functions have been explicitly introduced and explained in Ref. [39]). Up to now, various problems associated with dynamics of CNTs have been examined in the framework of NET of Eringen, including free vibrations [40–47], forced vibrations [48–50], vibrations of magnetically affected CNTs [51–57], dynamical analysis of CNTs in thermal environments [58–61], magneto-thermo-elastic vibrations of CNTs [62,63], and their nonlinear vibrations [64–67]. Further, vibrations of moving nano-scaled beam-like structures [68–70] and plate-like ones [71,72] have been of interest to nanotechnology researchers in recent years.

The atomistic-based approaches employed for mechanical analysis of individual SWCNTs would not be applicable to the modeling of VAJSWCNT due to their high computational efforts. In this view, appropriate continuum-based models would be very helpful in analyzing these important nanostructures. Joseph [73] characterized VAJSWCNTs from mechanical standpoint. The roles of tube configuration, diameter and height of tube, density of arrays, and tube distribution pattern on Young's modulus of the nanosystem are explained via finite element-based ABAQUS code. Kiani [74] examined forced vibration and potential instability of vertically aligned SWCNTs ensembles using nonlocal Rayleigh beam model. Both discrete and continuous models were established and the capabilities of the continuous model in vibrational analysis of highly populated nanosystems were displayed and discussed. Both in-plane and out-of-plane flexural behavior of membrane of vertically aligned SWCNTs were scrutinized by Kiani [75]. To this end, appropriate nonlocal Rayleigh, Timoshenko, and higher-order beam models were constructed and the roles of shear deformation and nonlocality on the predicted results were highlighted. Kiani [76] developed nonlocal discrete and continuous beam-like models to examine nonlocal vibrations of stocky VAJSWCNTs. The characteristics of transverse waves in VAJSWCNTs were addressed using discrete and continuous models based on the nonlocal Rayleigh, Timoshenko, and higher-order beam models [77]. The nonlocal dispersion curves of the nanostructure were obtained and the effects of influential factors on them were displayed. In another

Please cite this article in press as: K. Kiani, Nonlocal free dynamic analysis of periodic arrays of single-walled carbon nanotubes in the presence of longitudinal thermal and magnetic fields, Computers and Mathematics with Applications (2018), https://doi.org/10.1016/j.camwa.2018.02.033.