Physica E 70 (2015) 58–76

Contents lists available at ScienceDirect

Physica E

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

Vibrations of double-nanotube systems with mislocation via a newly developed van der Waals model

Keivan Kiani *

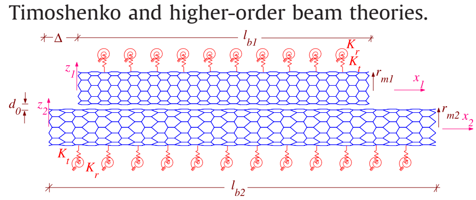
Department of Civil Engineering, K.N. Toosi University of Technology, P.O. Box 15875-4416, Valiasr Ave., Tehran, Iran

HIGHLIGHTS

- Frequency analysis of doubly parallel SWCNT with arbitrary configuration is studied.
- A new continuum-based vdW force model is developed accounting for mislocation.
- Nonlocal shear deformable beams are employed and their equations are obtained.
- The limitations of the nonlocal Timoshenko beam are explained for various BCs.
- The roles of crucial factors on first five frequencies are explored comprehensively.

GRAPHICAL ABSTRACT

A general configuration of a system of doubly parallel SWCNTs. Frequency analysis of doubly parallel SWCNTs embedded in an elastic matrix is of highly interest. To this end, a powerful meshfree method is implemented to solve the integral-partial differential governing equations resulted from the nonlocal Timoshenko and higher-order beam theories.



ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
28 January 2015
Accepted 2 February 2015
Available online 3 February 2015

Keywords:
Transverse vibration
Doubly parallel single-walled carbon nanotubes
Van der Waals force
Reproducing kernel particle method
Nonlocal shear deformable beams
Mislocation effect

ABSTRACT

This study deals with transverse vibrations of two adjacent-parallel-mislocated single-walled carbon nanotubes (SWCNTs) under various end conditions. These tubes interact with each other and their surrounding medium through the intertube van der Waals (vdW) forces, and existing bonds between their atoms and those of the elastic medium. The elastic energy of such forces due to the deflections of nanotubes is appropriately modeled by defining a vdW force density function. In the previous works, vdW forces between two identical tubes were idealized by a uniform form of this function. The newly introduced function enables us to investigate the influences of both intertube free distance and longitudinal mislocation on the natural transverse frequencies of the nanosystem which consists of two dissimilar tubes. Such crucial issues have not been addressed yet, even for simply supported tubes. Using nonlocal Timoshenko and higher-order beam theories as well as Hamilton's principle, the strong form of the equations of motion is established. Seeking for an explicit solution to these integro-partial differential equations is a very problematic task. Thereby, an energy-based method in conjunction with an efficient meshfree method is proposed and the nonlocal frequencies of the elastically embedded nanosystem are determined. For simply supported nanosystems, the predicted first five frequencies of the proposed model are checked with those of assumed mode method, and a reasonably good agreement is achieved. Through various studies, the roles of the tube's length ratio, intertube free space, mislocation, small-scale effect, slenderness ratio, radius of SWCNTs, and elastic constants of the elastic matrix on the natural frequencies of the nanosystem with various end conditions are explained. The limitations of the nonlocal Timoshenko beam theory are also addressed. This work can be considered as a vital step towards better realizing of a more complex system that consists of vertically aligned SWCNTs of various lengths.

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

http://dx.doi.org/10.1016/j.physe.2015.02.002

1. Introduction

The extraordinary physical, chemical, and mechanical properties of carbon nanotubes (CNTs) have attracted researchers from diverse range of fields to methodically explore their potential application in advanced technologies. To date, experimentally undertaken works have ensured the scientific communities that these newly synthesized materials can be efficiently used in drug and particle delivery systems [1–3], energy harvesting [4,5], nanoresonators [6–9], nanosensors (both physical and chemical) [10–12], and nano-/micro-electromechanical systems (NEMS/MEMS) [13–15]. In most of these applications, vibrations of CNTs play an important role and their dynamic mechanisms should be rationally understood. An individual single-walled carbon nanotube (SWCNT) is hard to believe to be employed for the above-mentioned purposes; however, ensembles of SWCNTs are commonly experimented to explore their efficiency for the considered jobs. This matter has been a driving force to investigate transverse vibrations of doubly parallel SWCNTs (DPSWCNTs) with an arbitrary configuration. Such a nanosystem can be imagined as the constitutive building block of vertically aligned ensembles of SWCNTs or as a simple constituent of even more complex systems such as haphazardly placed SWCNTs which are sometimes called jungles or forests of SWCNTs. As a result, a more rational modeling of such a nanosystem does not only increase our knowledge regarding their mechanical response, but also can be considered as a pivotal step towards better realizing of vibrations of more complex systems made of SWCNTs.

Due to the widely probable exploitations of CNTs and their composites, mechanical analysis and vibrations of individual SWCNTs have been extensively studied. For instance, free vibrations [16–18], vibrations due to moving nanoparticles [19–22], dynamic interactions with nanofluidics flow [23–25], mechanical sensing nano-objects [26–28] and unidirectional nanofluids [29], vibrations in the presence of magnetic fields [30–32], and their nonlinear vibrations [33–35] have been focus of attention for mechanical and structural engineers in recent years. Currently, free and forced vibrations of ensembles of SWCNTs have been examined via various nonlocal beam models [36–38]. Transverse vibrations of double-tube systems have been also examined [39,40], however, in the suggested models, the van der Waals (vdW) interactional forces between the atoms of two adjacent tubes were simply modeled by an elastic layer with one transverse constant. It implies that the role of the mislocation on dynamic response cannot be taken into account. These deficiencies and disabilities of the previously proposed models encouraged the author to revisit the problem in its most general vision, namely *doubly mislocated-parallel SWCNTs with arbitrary end conditions*. For this purpose, a novel model for evaluating the existing vdW force between two adjacent parallel tubes is suggested. In contrast to the past models in which the intertube vdW forces were considered by a constant, the present work suggests a more sophisticated model to capture such crucially interactional forces in which they play an important role in vibrations of such nanosystems. By this strategy, studying the role of mislocation on free vibration of the nanosystem is possible as it will be addressed comprehensively in the present work.

In most of the above-mentioned works, the vibrations of the nanosystems have been analyzed in the context of advanced theories of elasticity. It is chiefly related to this fact that at the atomic scale, vibration of each atom is influenced by the vibrations of its neighboring ones. Such a fact becomes crucial when the wavelength of the propagated waves is comparable with the atom bond length. Additionally, for bar-like or beam-like nanostructures when the ratio of the small-scale parameter to the nanostructure's length is not negligible, the classical theory of elasticity cannot capture the real or even near to exact vibration patterns of the nanostructure. These evidences are the most convincing reasons for exploiting advanced continuum mechanics to explore vibrations at the nanoscale. One of the most popular advanced theories is that developed by Eringen [41–43], called nonlocal continuum field theory. This theory explains that the state of stress or strain at each point of the continuum does not only depend on the stress or strain of that point, but also on the stresses or strains of its neighboring points. Such an issue is incorporated into the constitutive equations of the matter by a so-called small-scale factor. Generally, its magnitude is determined by comparing the obtained dispersion curves from the nonlocal model and those of a reliable atomic model. The magnitude of this parameter differs from one problem or matter to another one. Recent investigations [19,22] show that this parameter has a substantial effect on the mechanical behavior of stocky beam-like nanostructures. However, for slender nanosystems, its influence on their transverse dynamic response vanishes. In such a case, the discrepancies between the predicted results by the nonlocal model and those of the classical one would reduce.

In the present work, transverse vibration of DPSWCNTs in the context of the nonlocal continuum theory of Eringen is of interest. The most well-known shear deformable beam theories, namely Timoshenko [44,45] and higher-order of Reddy–Bickford [46,47], are adopted. Using Hamilton's principle, the equations of motion of the nanosystem at hand on the basis of these beam models are derived. An efficient numerical solution is suggested, and the natural frequencies of the nanosystem are obtained. The effects of nonlocality, various geometrical parameters associated with the nanosystem, and the interactions of the nanosystem with its surrounding elastic medium on the natural frequencies are comprehensively addressed.

2. Definition of the nanomechanical problem

Consider two parallel SWCNTs at the vicinity of each other. For mechanical modeling of such a system, each tube is replaced by an equivalent continuum structure (ECS). The ECS is a nano-scaled structure whose length and mean radius are identical to the length and radius of the parent tube, and its wall's thickness is 0.34 nm [48,49]. The intertube distance is denoted by d, the tubes lengths are l_{b_i}, their mean radii are r_{m_i}; $i = 1, 2$, their cross-section areas and moments inertia are denoted by A_{b_i} and I_{b_i}, respectively, and the mislocation of one tube with respect to the another one is represented by Δ (see Fig. 1). The mechanical properties of the ECSs are identified by the parameters ρ_{b_i}, E_{b_i}, G_{b_i}, and ν_{b_i} in which in order represent the density, Young's modulus, shear elastic moduli, and Poisson's ratio such that $G_{b_i} = E_{b_i}/2(1 + \nu_{b_i})$. Each tube interacts transversely and rotationally with its surrounding elastic medium. Such effects have been taken into account in modeling of the problem by a two-parameter elastic layer whose transverse and rotational stiffness are equal to K_t and K_r, respectively. Additionally, the nanotubes interact with each other due to the existing vdW forces between their constitutive atoms. Using nonlocal shear deformable beam theories, free transverse vibrations of such a nanosystem with various end conditions are of our interest.

For this purpose, a novel model for considering the intertube vdW forces is proposed in the next part. Subsequently, using Hamilton's principle, the strong form of the equations of motion of the elastically embedded nanosystem is obtained by establishing the models based on the nonlocal Timoshenko beam theory (NTBT) and the nonlocal higher-order beam theory (NHOBT).