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Nanomechanical sensors based on elastically supported double-walled carbon nanotubes

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ABSTRACT

Carbon nanotubes are anticipated to have potential applications in nanosensor technology; however, their usage under various boundary conditions has not been thoroughly revealed. In this article, we are seeking for appropriate numerical models to bridge such a scientific gap for double-walled carbon nanotubes (DWCNTs) as nanomechanical sensors. Some nonlocal beam models are developed for exploring the vibration performance of embedded DWCNTs in an elastic matrix due to the arbitrarily added nanoparticles. The nonlocal continuum theory of Eringen is employed, and the governing equations of each model are constructed by considering the lateral and rotary inertial effects of the attached nanoparticles. Since examining the problem for a wide range of boundary conditions is of particular interest, an effective meshless method is exploited. For the proposed numerical models, a comparison study along with a convergence check is carried out and reasonably good agreements are achieved. The key factor in mechanical performance of DWCNTs for sensing the nanoparticles is the alteration of their natural flexural frequencies. A fairly conclusive study is then conducted to determine the influences of the crucial factors on the frequency shift of DWCNTs. The obtained results explain the potential applications of DWCNTs as mass nanosensors for a diverse range of boundary conditions.

1. Introduction

Thanks to the exceptional properties of carbon nanotubes (CNTs), numerous potential applications for them have been proposed and examined during recent years. In combination of physical and chemical properties, CNTs could be applicable in various branches of engineering sciences, such as transistors and emitters [1–3], thermal acoustic instruments [4], composite materials for wind turbine, bullet-proof vests, body armors, chemical/biochemical sensors, and strain and mechanical sensors [5–15]. From applied mechanics point of view, the latter application for a special class of CNTs, namely double-walled carbon nanotubes (DWCNTs), is of concern in this study.

A nanosensor is a nanodevice that acts in response to a physical, chemical or biological parameter and converts its response into a signal or an output. The market drivers, engineering and scientific communities relevant to sensors point toward progress of nanosensors constructed from constituents for nanoscale sampling, pre-concentrating, and signal analysis. On account of the high ratio of the elasticity modulus to the mass density of CNTs, they have been increasingly paid attention to for the last abovementioned task. There exist evidences indicating that the fundamental frequencies of multi-walled carbon nanotubes

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(MWCNTs) are in the range of several gigahertz [16–18] or even terahertz [19–21]. This fact has brought CNTs as a new generation of oscillators. Based as mass nanosensors, with outstanding sensing of nano-sized objects, for an extensive range of applications.

A DWCNT consists of two coaxial cylindrically rolled graphene sheets in the vicinity of each other. The atoms of two neighboring walls are interacted with each other due to van der Waals forces. Such attractive forces keep tightly two walls. When a nanoparticle becomes close to the outer surface of a DWCNT, it could be absorbed by its outermost tube due to the existing physical attraction forces. Therefore, the resonant frequencies of the DWCNT change according to the mass weights of the attached nanoparticles as well as the position(s) of the contact point(s). Additionally, some structural aspects and environmental factors associated with the DWCNT, such as ratio of length to diameter, ratio of diameter to the effective thickness of the tube wall, existing initially axial forces, stiffness of the surrounding environment, and boundary conditions of two ends of each tube are among verity parameters influencing on the alteration of the frequency change of the DWCNT due to addition of nanoparticles. For optimal design as well as characterization of vibration behavior of DWCNTs based nanomechanical sensor, a true understanding of the effects of the influential parameters on the free dynamic response of such nanosensors would be helpful. In this study, it is attempted to explore the influences of various factors on the change of fundamental frequency of the understudy nanostructure-based nanomechanical sensor.

Before brief reviewing of the related articles, it is emphasized that understanding the true mechanism of the lateral vibration of DWCNTs is a preliminary step in understanding characterization of the dynamic analysis of them as nanomechanical sensors. Until now, free and forced vibrations of DWCNTs have been studied by many researchers [22–28] and an inclusive knowledge regarding such phenomena has been provided. Concerning frequency analysis of CNTs as mass nanosensors, Li and Chou [29] investigated vibration behavior of both single- and doubled-walled carbon nanotubes using the molecular-structural-mechanics method. The obtained results displayed that the predicted resonant frequencies of the atomistic-based model are averagely 50% higher than those of the classical continuum-based shell model. Elishakoff et al. [30] studied free dynamic response of a cantilevered DWCNT with an attached bacterium at the tip of the innermost or outermost tube as a biosensor. By considering both the lateral and rotational inertial effects of the attached bacteria, classical Euler–Bernoulli beam theory was adopted for the frequency shift of the nanosensor using the finite difference method. Using the transfer function method (TFM), Shen et al. [31] examined the vibration of DWCNTs with an attached mass as nanomechanical sensors employing the nonlocal Euler-Bernoulli beam model. The undertaken work was restricted to the fully clamped (i.e., bridged) DWCNT with an attached nanoparticle undergoing initial axial forces in both tubes. The effects of initial axial force as well as weight and location of the attached nanoparticle on the frequency shift of the DWCNT were addressed. In another work, Shen et al. [32] studied vibration behavior of DWCNT-based mass sensor via TFM when the mass was attached to the tip of the innermost tube. The lengths of the tubes were not the same, but both tubes were modeled according to the nonlocal Timoshenko beam model. As is seen in the literature, the mechanical aspects of slender and stocky DWCNTs with different boundary conditions as nanomechanical sensors have not been thoroughly realized. Possibly, it is related to the complexities that appear in developing analytical solutions for the governing equations. According to the literature, application of analytical approaches to the problem at hand is restricted to DWCNTs as nanomechanical sensors with simply supported ends or fully clamped boundary conditions.

In the lack of analytical solutions, efficient numerical methods would be a good alternative. The reproducing kernel particle method (RKPM) is a renowned approach of meshless schemes' family. This methodology was developed by Liu et al. [33,34] to treat shortcomings of the smooth particle hydrodynamics (SPH) method. The major feature of this method with respect to SPH is the incorporation of correction functions into the formulations of the shape functions. By this strategy, the performance and smoothness of RKPM in regions near to the boundaries of the problem are highly improved. In this newly developed method, the spatial domain of the problem is discretized by appropriate shape functions associated with the particles of the RKPM. Based on the completeness condition, the shape functions of the RKPM's particles are numerically evaluated at the desired points according to the dilation parameter as well as the chosen window and base functions. Higher-order base functions as well as window functions yield higher-order shape functions. However, increasing the order of the base function can significantly magnify the cost of the shape functions' generation; besides, the accuracy of the generated shape functions would lessen due to a large amount of calculations. The suitably higher-order shape functions provide RKPM as an effective approach for those problems suffer from discontinuity, sharp variation of fields, or governing equations with higher-order spatial derivatives. RKPM has been applied to many engineering problems such as structural dynamics, large deformation solids, fluid mechanics, micro-electro-mechanical systems, single-walled carbon nanotubes, and nanowires [33,35–44].

Herein, we adopt RKPM to discretize the unknown fields pertinent to the proposed nonlocal models for mechanical modeling of DWCNTs as mass sensors. The potential application of DWCNTs as mass nanosensors is examined in the framework of nonlocal continuum theory of Eringen. In doing so, the nanostructure with the attached masses is modeled by using the nonlocal Rayleigh beam theory (NRBT), nonlocal Timoshenko beam theory (NTBT), and nonlocal higher-order beam theory (NHOBT). Both the translational and rotary inertial effects of the attached nanoparticles are incorporated into the governing equations of the proposed models. As will be shown, finding explicit solutions to the equations of motion of the elastically supported DWCNT-based mass sensor is a very difficult task. Therefore, RKPM is implemented to determine the unknown fields of each model. By solving the set of eigenvalue equations of each model, the natural frequencies of the elastically supported DWCNT with arbitrarily attached nanoparticles are determined. The most important feature of addition of nanoparticles to a DWCNT is the alteration of its natural frequencies. Hence, investigation of the influential factors on the change of the natural frequencies of the DWCNT would be vital for optimal design of them as nanosensors. A moderately comprehensive parametric study is then conducted to reveal the role of various factors on the frequency shift of the DWCNT due to the addition of nanoparticles. Through such studies,