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Full Length Article

Damped forced vibration analysis of single-walled carbon nanotubes resting on viscoelastic foundation in thermal environment using nonlocal strain gradient theory

Mohammad Malikan [a,*], Van Bac Nguyen [b], Francesco Tornabene [c]

[a] Department of Mechanical Engineering, Faculty of Engineering, Islamic Azad University, Mashhad Branch, Mashhad, Iran
[b] Department of Mechanical Engineering and the Built Environment, College of Engineering and Technology, University of Derby, Derbyshire, United Kingdom
[c] Department of Civil, Chemical, Environmental, and Materials Engineering, University of Bologna, Bologna, Italy

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ABSTRACT

In this paper, the damped forced vibration of single-walled carbon nanotubes (SWCNTs) is analyzed using a new shear deformation beam theory. The SWCNTs are modeled as a flexible beam on the viscoelastic foundation embedded in the thermal environment and subjected to a transverse dynamic load. The equilibrium equations are formulated by the new shear deformation beam theory which is accompanied with higher-order nonlocal strain gradient theory where the influences of both stress nonlocality and strain gradient size-dependent effects are taken into account. In this new shear deformation beam theory, there is no need to use any shear correction factor and also the number of unknown variables is the only one that is similar to the Euler-Bernoulli beam hypothesis. The governing equations are solved by utilizing an analytical approach by which the maximum dynamic deflection has been obtained with simple boundary conditions. To validate the results of the new proposed beam theory, the results in terms of natural frequencies are compared with the results from an available well-known reference. The effects of nonlocal parameter, half-wave length, damper, temperature and material variations on the dynamic vibration of the nanotubes, are discussed in detail.

1. Introduction

Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure; they are the first generation of the nano products that were discovered in 1991 [1]. The CNTs are made of twisted graphite sheets with a honeycomb-like structure. These nanotubes are very long and thin and also are stable, resistant, and flexible structures [2]. If the CNT only contains a pipe of graphene, it is called a single-walled carbon nanotube (SWCNT), and if it contains multiple rolled layers of graphene (concentric tubes), it is called a multi-wall carbon nanotube (MWCNT) [3,4]. The SWCNT is remarkably strong and hard [5], excellent in conducting electric current and directing heat [6–8], which has led to the wide use of these materials in the electronics industry, and one useful application is in the development of the first intermolecular field-effect transistors [9,10]. The MWCNT has many potential applications, from waterproof and tear resistant cloth fabrics, concrete and steel like applications based on the property of strength, electrical circuits based on the property of electrical conductivity, sensors based on the property of thermal conductivity, vacuum proof food packaging, and even as a vessel for delivering drugs. The carbon nanotube promises a bright future in cellular experiments because they can be used as nano-pipes to distribute very small volumes of fluid or gas into living cells or on surfaces [11–13].

These are nanostructures that are unique in their size, shape, and remarkable physical properties. To exploit the industrial amazing properties of such materials, it can be highly recommended that their mechanical behavior and properties should be investigated. In recent years, these intriguing mechanical properties have sparked much excitement and a large amount of studies by researchers around the world has been dedicated to their understanding. Malikan et al. [14] studied the nonlinear stability of bilayer graphene nanoplates subjected to shear and thermal forces in a medium using nonlocal elasticity theory and numerical solutions. In addition, Malikan investigated the stability of a micro sandwich plate with graphene coating using the refined couple

* Corresponding author.
E-mail addresses: mohammad.malikan@yahoo.com (M. Malikan), vb.nguyen@derby.ac.uk (V.B. Nguyen), francesco.tornabene@unibo.it (F. Tornabene).

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stress theory [15] and buckling of graphene sheets subjected to nonuniform compression based on the four-variable plate theory using an analytical approach [16]. Yang et al. [17] examined the natural frequency of nonlinear free vibration of polymer composite beams reinforced with graphene nanoplatelets. Ansari et al. [18] studied coupled natural frequency analysis of post stability functionally graded micro/nanobeams on the basis of the strain gradient theory. Wang et al. [19] presented exact modes for post stability characteristics of nonlocal nanobeams in a longitudinal magnetic field. Analytical solutions for thermal vibration of nanobeams were studied by Jiang and Wang [20]; in this study, the Euler beam was modeled using nonlocal elasticity theory, and the beam was subjected to axial thermal forces. Xiang et al. [21] used nonlocal elasticity theory for studying nonlinear free vibration of double-walled carbon nanotubes based on Timoshenko beam theory. Li and Hu [22] presented buckling analysis of size-dependent nonlinear beams using nonlocal strain gradient theory. Guo et al. [23] developed a lower-order nonlocal strain gradient theory for evaluating vibration of nanobeams. The vibration of thermally post-buckled carbon nanotube-reinforced composite beams resting on elastic foundations was examined by Shen et al. [24]. Beni et al. [25] studied the vibration of shell nanotubes using nonlocal strain gradient theory and molecular dynamics simulation; in this study, a lower-order nonlocal strain gradient theory combining with first-order shear plate theory was adopted in order to obtain governing equations. Wang et al. [26] presented the nonlinear vibration of carbon nanotubes placed on the visco-Pasternak foundation under excitation frequency by nonlocal continuum theory. Chaudhari and Lal [27] investigated the nonlinear free vibration of elastically nanotubes reinforced composite beams resting on elastic foundation in thermal environment. They used higher-order shear deformation beam theory in conjunction with finite element models. The electro-mechanical vibration of single-walled nanotubes considering piezoelectric effects has been studied by Kheibari and Beni [28]. They modeled nanotubes as a thin shell model with the help of couple stress theory and then the governing equations were solved using Kantorovich method. Malekzadeh et al. [29] introduced a pre-twisted functionally graded (FG) carbon nanotube reinforced composite beam exposed to a vibrational condition based on the higher-order shear deformation theory of beams by considering the temperature dependence of material properties and the initial thermal stresses. The SWCNTs with several distributions reinforced the square FG-beam in thermal environment was considered and the Reddy's third-order shear deformation beam theory was employed to derive governing equations. Jiang et al. [30] analyzed the forced vibration of SWCNTs using molecular dynamics simulation based on one and three-segment Timoshenko beam models. Chang [31] studied the stochastic dynamics behavior of SWCNTs with random material properties resting on a nonlinear damper and subjected to an axial magnetic field without using any dynamics load. The nonlocal elasticity theory was applied to take small scale effects into consideration. The Monte Carlo simulation, Galerkin's and the multiple scale methods were utilized to predict the response of nonlinear governing equations which were derived from the Hamilton's principle. Jiang and Wang [32] studied the vibration of double-walled carbon nanotubes bridged on a silicon substrate and the nanotubes were modeled with Timoshenko beam model. Ren et al. [33] modeled nanotubes as functionally graded porous beams under free vibrational conditions. They used a two-variable refined beam theory combined with the nonlocal strain gradient theory to formulate size-dependent influences. Navier solution method was adopted to solve the frequency equation and the most significant results revealed that the presence of porosity could increase or decrease the natural frequency based on the grading index values. There have also been many valuable research in which carbon nanotubes have been investigated in several conditions [34–42].

In this theoretical work, a new shear deformation beam theory developed by reducing the unknown variables from a regenerated first-order shear deformation theory is used for the vibration analysis of a single-walled carbon nanotube. The single-walled carbon nanotube (SWCNT) is modeled as an elastic beam resting on a viscoelastic foundation in the thermal environment and subjected to a transverse dynamic harmonic load in order to evaluate excitation frequencies and thermo-vibrational behavior. Both stress nonlocality and strain gradient size-dependent influences are examined by using a higher-order nonlocal strain gradient theory. Furthermore, Navier's analytical approach is employed to solve the frequency equations by assuming simply-supported boundary conditions for both ends of the beam. The results obtained by the new theory are validated against the results available in literature.

2. Mathematical modeling

Fig. 1 displays a realistic model for a SWCNT resting on a viscoelastic foundation in a thermal environment subjected to the uniform transverse harmonic dynamic load. The tube has the length L, diameter d and thickness h parallel to x and z-axes of the right-hand coordinate system, respectively.

Heretofore, many methods have been used for investigation of mechanical behavior of beams. The simplest theory for analysis of beams is the classical hypothesis which is based on Euler-Bernoulli's assumptions that the influences of transverse shear deformation are not taken into account. In this theory, it is assumed that during deformation, the cross section of the beam is to remain planar and normal to the deformed axis of the beam. This covered the case for small deflections of a beam that are subjected to lateral loads only and it is an appropriate theory to study thin beams (Euler-Bernoulli beam). However, due to the regardless of the shear and transverse strains along the thickness, using this beam theory is accompanied with errors in predicting the deformation or transient response of the beam in moderately thick and thick beams (Timoshenko's beam). In order to reduce this error in the analysis of relatively thick beams, another theory known as shear deformation one was introduced. In this theory, it is assumed that during deformation, there is a rotation between the cross section and the deformed axis of the beam as the transverse shear effects are taken into consideration. Although these shear deformation theories could produce reasonable results in the analysis of moderately thick beams, they are still not close to exact results due to the non-consideration of the effect of transverse strains ($\varepsilon_z = 0$). The first-order shear deformation theory is accompanied with a serious error for which the shear correction factor has been used. This means that the shear stress along the thickness of the beam is assumed to be constant, which is not realistic. To overcome this problem and to achieve the accuracy in predicting the beam behavior, a new first-order shear deformation beam theory has been introduced. According to the first-order shear deformation theory, the displacement field at any material point in the beam could be defined as follows [14]:

$$\begin{Bmatrix} U(x,z,t) \\ V(x,z,t) \\ W(x,z,t) \end{Bmatrix} = \begin{Bmatrix} u(x,t) + z\varphi(x,t) \\ 0 \\ w(x,t) \end{Bmatrix} \tag{1a-c}$$

In Eq. (1), the vector quantities of the neutral axis at directions of x and z are u and w, respectively. Furthermore, for defining of the swirl of beam elements around the x axis, φ is used. First of all, the simple first-order shear deformation theory (S-FSDT) is recalled where the deflection parameter could be expressed as follows [43–45]: