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Forced vibration of two coupled carbon nanotubes conveying lagged moving nano-particles

Lei Lü, YuJin Hu*, XueLin Wang

School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China

HIGHLIGHTS

- Two nano-particle conveying carbon nano-tubes are coupled.
- A lag of time exist between the nano-particles conveying in the tubes.
- With proper lag, the maximum vibration amplitudes of both tubes could be reduced.

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ABSTRACT

The transverse deflections of the nano-tubes are important issues in engineering applications. However, the researches on the deflection suppression are still insufficient. This paper focused on the investigation of the transverse vibration of double carbon-nano-tubes (DCNTs) which were coupled through elastic medium. Both tubes were conveying moving nano-particles and their ends were simply supported. The system equations were discretized by applying Galerkin expansion method, and numerical solutions were obtained. Several system parameters were studied to investigate the dynamics of the tubes. The results indicated that, because of the lag, the maximum transverse deflections of both coupled tubes can be reduced.

1. Introduction

Carbon nanotubes (CNTs) are cylindrical macromolecules composed of carbon atoms, which are widely used in many applications in nanotechnology [1], chemical, electronics [2], optics [3] and other fields of materials science [4–6]. Due to its excellent mechanical [7,8], electrical [9] and thermal [10] properties, CNTs become more and more important in modern industries. Its potential and important applications in atomic-force microscopes, field emitters, nano-actuators, nano-motors, nano-bearings, nano-springs, nano-fillers for composite materials, and nano-scale electronic devices [11] were all widely studied.

In the nonlocal elasticity theory, the size effects captured by assuming the stress components at a point x were dependent not only on the strain components at the same point x, but also on all other points in the domain [12]. The nanotubes had been of considerable interest in view of the rapid progress of nanotechnology [13], and CNTs were used as molecular channels for the drug delivery systems and the transportation of nanoparticles, such as water and protons [14]. Kiani and Mehri [15] carried out the dynamic analysis of nanotube structures under excitation of a moving nanoparticle, using nonlocal continuum theory of Eringen. The nanotube was modeled by an equivalent continuum structure (ECS) according to the nonlocal Euler Bernoulli, Timoshenko and higher order beam theories. Şimşek [16] investigated the dynamic behavior of a single-walled carbon nanotube subjected to a moving harmonic load based on Eringen's nonlocal elasticity theory. Şimşek [17] performed the dynamic analysis of an embedded single-walled carbon nanotube traversed by a moving nanoparticle based on the nonlocal Timoshenko beam theory, including transverse shear deformation and rotary inertia. On the other hand, the nanotube conveying fluid was also widely studied. Wang et al. [18] developed a conveying fluid single-walled nanotube considering the thermal effect. And they concluded that the temperature change on the instability of SWCNTs conveying fluid is significant. Rasekh and Khadem [19] investigated the influence of internal moving fluid and compressive axial load on the

* Corresponding author.
E-mail address: yjhu@mail.hust.edu.cn (Y. Hu).

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nonlinear vibration and stability of embedded carbon nanotubes. Soltani and Farshidianfar [20] developed a nonlinear model for the fluid-conveying nanotube, which was embedded in a Pasternak-type foundation. Jannesari et al. [21] concerned with viscous and nonlocal effects on the structural stability of single-walled carbon nanotube conveying fluid. The nonlinear Donnell shallow shell formulations were developed to model nonlocal effects.

Oniszczuk [22] analyzed undamped forced transverse vibrations of an elastically connected complex double-beam system. The action of stationary harmonic loads and moving forces were considered. Abu-Hilal [23] studied the dynamic response of a double-beam system traversed by a constant moving load. The two simply supported prismatic beams were identical, parallel one upon the other and connected continuously by a viscoelastic layer. Wang et al. [24] investigated the natural vibrations and buckling instability of double-walled carbon nanotubes (DWCNTs) conveying fluid with simple supports at both ends, by using a multi-elastic beam model in which the intertube radial displacements and the related internal degrees of freedom were considered. Murmu and Adhikari [25] studied a double nanorod system's longitudinal vibration behavior considering nonlocal effects, which considerably influenced the axial vibration of the system. Şimşek [26] studied a double carbon nano-tubes system, with one of the tube carrying a moving nano-particle. The system was analyzed both analytically and numerically, demonstrated that the classical beam models were not suitable in modeling carbon nanotubes with small aspect ratio and the nonlocal effects should be taken into account. Further more, the velocity of the nano-particle and the coupling stiffness had significant effects on the dynamic behavior of the system. Ghorbanpour Arani and Roudbari [27] investigated the nonlocal piezoelastic surface effects on the visco-Pasternak coupled boron nitride nano-tube system under a moving nano-particle. The tubes' axial and longitudinal vibration behaviors were studied. They demonstrated that the normalized dynamic deflections obtained by using the classical beam theory were smaller than those obtained by the nonlocal beam theory. The influence of the smart controller was proved on the non-dimensional fundamental longitudinal frequency.

So far, in most of the studies of the double-nano-tubes system, there was only one tube conveying a moving nano-particle or fluid, and the other tube was free from external excitation, but excited indirectly through the coupling. In spite of many publications devoted to these subjects, a study about dynamics of coupled tubes both conveying moving loads, either the same or different, is still lacking. Moreover, the moving particles may enter the tubes at different time. The objective of the present paper is to establish a double tubes system and study its transverse vibration behavior, with both tubes conveying moving nano-particles loads.

2. Non-global coupled nano-tube model considering the nonlocal effects and non-global coupling

Fig. 1 depicts two single-walled carbon nano-tubes(SWCNT) conveying moving nano-particles. The tubes are assumed to be simply supported at both ends and are coupled through an elastic medium between them. The effect of gravity is negligible and not considered in. As the SWCNT is supposed to be slender, the beam theory is applied to simulate the vibrational behavior in the model. The elastic medium and the force due to nanooptomechanical effect or van der Waals force between the two tubes are substituted by the axially distributed springs (stiffness K) attach to the tubes, as shown in the figure. The tubes are assumed to have length L, diameter d and the effective thickness of the tube wall t_b. The cross section of the tube is A.

Using Newton's law, a basic and simple linear governing equation of transverse motion of a SWCNT conveying a moving particle can be written as [16], which has been widely used:

$$EIw^{(4)} + \rho A\ddot{w} - \rho A(e_0a)^2\ddot{w}'' = p - (e_0a)^2p'' \tag{1}$$

where "˙" denotes the derivative of time and " ′ " denotes the derivative of the axial coordinate x. $w(x, t)$ is the transverse deflection of the SWCNT. E is the modulus of elasticity, I is the moment of inertia. ρ is the mass density of the nano-tube. e_0 is a constant appropriate to each material, a is an internal characteristics length [16], such as lattice parameter and granular distance. As widely studied through analysis and experiments, the nonlocal parameter e_0a is very important in determining the nonlocal effects of the CNTs. The value of e_0a is critical in the studies and must not be neglected. A conservative estimate given by Wang [28] is $e_0a \le 2$ nm for an SWCNT. The nano-tube is subjected to conveying a moving nano-particle modeled as a moving constant load P. The moving load $p(x, t)$ can be written as follows:

$$p(x, t) = P{\cdot}\delta(x - x_p) \tag{2}$$

where P is the amplitude of the load. $\delta(_*)$ is the Dirac-Delta function, x_p is the coordinate of the moving load.

In this study, two linearly coupled SWCNTs make up a double-carbon-nano-tubes (DCNTs) system as shown in Fig. 1. The elastic medium is assumed to be massless and simplified as linear springs distributed along the tube length and connects the two tubes continuously. Both tubes are basically equivalent. The tubes are conveying the same moving nano-particles, which are of the same moving velocity. The nano-particles enter the tubes at different time: the nano-particle enters the secondary tube before another nano-particle moves out in the primary tube. The partial differential equations of the DCNTs for the transverse vibration of the

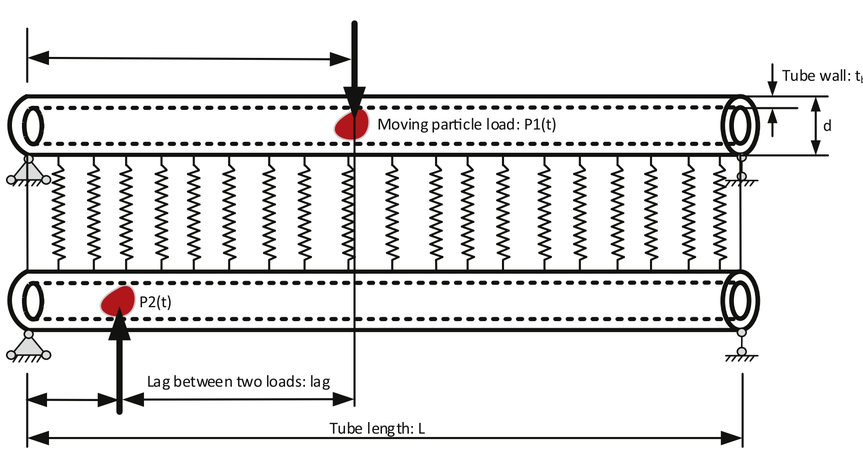

Fig. 1. Non-globally coupled double carbon nano-tubes, both carrying moving nano-particle loads.