Mechanics Research Communications 60 (2014) 33–39

Contents lists available at ScienceDirect

Mechanics Research Communications

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

Magnetically affected single-walled carbon nanotubes as nanosensors

Keivan Kiani *

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

ARTICLE INFO

Article history:
Received 21 April 2013
Received in revised form 30 November 2013
Accepted 9 May 2014
Available online 22 May 2014

Keywords:
Nanosensor
Magnetically affected single-walled carbon nanotube
Nonlocal Rayleigh beam
Frequency shift

ABSTRACT

The influence of longitudinal magnetic fields on the nanomechanical sensing behavior of single-walled carbon nanotubes (SWCNTs) is of interest. To this end, a nonlocal mathematical model is proposed to study alteration of the fundamental flexural frequency of a magnetically affected SWCNT due to an arbitrarily added nanoparticle. The explicit expressions for the frequency shift of magnetically affected cantilevered and bridged SWCNTs due to the addition of a nanoparticle at the tip and midspan points are obtained. The predicted results reveal that the mechanical sensing of SWCNTs is generally enhanced by application of the longitudinal magnetic field.

1. Introduction

To date, the rising demand for high qualified automation, security, and control of the environments has led to utilize materials of superior magneto-electro-mechanical behaviors as sensors. Among various newly synthesized materials, carbon nanotubes have been in focus of attention of many technologists and scientists as potentially applicable nanosensors. This fact is mainly related to their extraordinary chemical and physical properties (Ruoff and Lorents, 1995; Salvetat et al., 1999; Thostenson et al., 2001). Since all atoms of single-walled carbon nanotubes (SWCNTs) are on the surface, they have the largest surface area to volume ratio in compare to other carbon-based materials, approximately 3×10^6 m^2/kg (Robertson, 2004). Such a special characteristic of SWCNTs have been provided them as a potential candidate for chemical sensors (Snow et al., 2005). Other possible applications of SWCNTs which are of interest to nanotechnologists are acoustic (wave velocity, wave amplitude) sensors (Yu et al., 2006; Sivaramakrishnan et al., 2008), thermal (temperature, thermal conductivity) sensors (Agarwal et al., 2008; Selvarasah et al., 2007), radiation sensors (Rao et al., 2008) and mechanical (force, stress, mass) sensors (Stampfer et al., 2006a,b; Helbling et al., 2009; Hierold et al., 2007; Jensen et al., 2008). In this article, the latter potential usage of SWCNTs in the presence of a longitudinal magnetic field is methodically studied.

The usage of an individual SWCNT as a nanomechanical sensor has been theoretically examined by many researchers (Li and Chou, 2004; Wu et al., 2006; Chowdhury et al., 2009; Joshi et al., 2010; Aydogdu and Filiz, 2011; Shen et al., 2012a,b; Murmu and Adhikari, 2012; Kiani et al., 2013). In these works, the capabilities of SWCNTs in sensing of nanoscale objects were explored by monitoring the alteration of the frequencies of the equivalent continuum structure (ECS). In the above-mentioned works, the works of Li and Chou (2004), Wu et al. (2006), Chowdhury et al. (2009) were based on the local continuum theory whereas the frequency analyses of the problem in the remainder ones were performed via nonlocal elasticity theory of Eringen (Eringen, 1966, 1972, 2002). The main privilege of the latter theory to the local one is the consideration of the inter-atomic bonds in its constitutive equations through a crucial parameter called small-scale. From physics points of view, it implies that the stress state of each point of the ECS relies on stresses of the neighboring points. Through various comparison studies, it has been also proved that by choosing an appropriate value for the small-scale parameter, the nonlocal continuum theory can successfully capture the near to exact dispersion curves of the nanostructures (Duan et al., 2007; Kiani, 2010b; Ansari et al., 2011). Therefore, such an advanced theory of elasticity is employed for the problem under examination.

* Tel.: +98 21 88779473; fax: +98 21 88779476.
E-mail addresses: k_kiani@kntu.ac.ir, keivankiani@yahoo.com

http://dx.doi.org/10.1016/j.mechrescom.2014.05.005

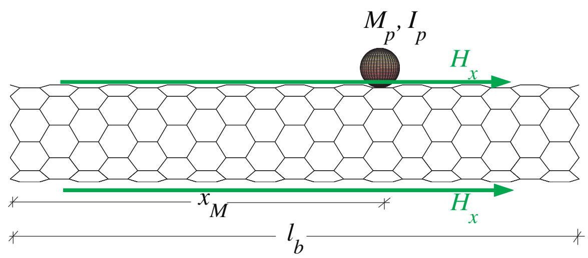

Fig. 1. A magnetically immersed SWCNT for sensing an arbitrarily attached nanoparticle.

As it is obvious from the literature, in the previous works, a methodology for enhancing the sensitivity of SWCNTs had not been pointed out. In the present work, application of a longitudinal magnetic field as an efficient technique for improving the sensitivity of SWCNTs is proposed. Until now, the effects of dynamic and steady longitudinal magnetic fields on vibrational characteristics of nanostructures have been studied (Wang et al., 2010; Kiani, 2012a,b,c, 2014; Narendar et al., 2012; Murmu et al., 2012). However, the role of the applied magnetic field on the performance of SWCNTs in sensing of nanoparticles has not been revealed. To bridge this scientific gap, this work is devoted to calibrate magnetically influenced SWCNTs in terms of the strength of the applied magnetic field as well as other characteristics of the system of SWCNT-nanoparticle. By using nonlocal Rayleigh beam theory, the equations of motion of magnetically affected SWCNTs for sensing an arbitrary nanoparticle is obtained. The explicit expression of the flexural frequency of the nanosystem is derived. For two potential cases as nanosensors, namely cantilevered and bridged SWCNTs, the frequency shift as well as the sensitivity ratio of the magnetically affected SWCNT are analytically extracted based on the proposed model. The influence of the mass weight of the added nanoparticle as well as the magnetic field strength on the frequency shift and sensitivity of both cantilevered and bridged SWCNTs are studied.

2. Definition of the nanomechanical problem

A SWCNT of length l_b exposed to a longitudinal magnetic field of strength H_x is aimed to be used as a nanomechanical sensor (see Fig. 1). For modeling of the nanostructure, an equivalent continuum structure (ECS) pertinent to the considered SWCNT is employed. The ECS is a circular cylindrical shell of density ρ_b, cross-sectional area A_b, length l_b, moment inertia of the cross-section I_b, Young's modulus E_b, and magnetic permeability η. The dimensions of the ECS are determined such that most of its dominant longitudinal and torsional frequencies would be identical to those of the SWCNT. For an ECS of length equal to that of the SWCNT, the works of Gupta and Batra (2008) and Batra and Gupta (2008) revealed that the ECS is a single-walled cylindrical shell of thickness 0.34 nm and mean radius identical to that of the SWCNT. For nanomechanical sensing of a nanoparticle of mass M_p and moment inertia I_p by a SWCNT, the alteration in the natural flexural frequency of the SWCNT is a key factor that should be appropriately determined.

In the following part, using a nonlocal continuum beam model, the fundamental frequency of the magnetically affected nanostructure with an added nanoparticle at an arbitrary point is evaluated.

3. Theoretical formulations

3.1. Nonlocal equations of motion

According to the hypothesis of the Rayleigh's beam model, the governing equation of a SWCNT with an attached nanoparticle for free vibration reads (Kiani et al., 2013):

$$\rho_b A_b \ddot{w} - \rho_b I_b \ddot{w}_{,xx} + \left(M_p \ddot{w} - I_p \ddot{w}_{,xx}\right) \delta(x - x_M) - M^{nl}_{b,xx} = M_p g \delta(x - x_M) + q_w, \tag{1}$$

where $\dot{[.]}$ and $[.]_{,x}$ in order represent the first derivatives of [.] with respect to the time and space parameters, x_M is the position of the attached nanoparticle, g is the gravitational acceleration, and $\delta(x)$ denotes the Dirac delta function, $w = w(x, t)$ and $M^{nl}_b = M^{nl}_b(x, t)$ are the dynamic transverse displacement and nonlocal bending moment fields of the SWCNT, respectively, and $q_w = \eta A_b H_x^2 w_{,xx}$ for a SWCNT acted upon by a longitudinal magnetic field (Wang et al., 2010; Narendar et al., 2012; Kiani, 2014). It is worth-mentioning that Eq. (1) is somehow similar to that constructed based on the Euler–Bernoulli beam theory (Elishakoff et al., 2011). The main privilege of the Rayleigh beam model with respect to the Euler–Bernoulli beam theory is the incorporation of the rotary inertia into the formulations of the beam-like structure. Thereby, the predicted results by this model would be more accurate in compare to those of the Euler–Bernoulli beam theory. In the context of the nonlocal continuum theory of Eringen (Eringen, 1966, 1972, 2002), the nonlocal bending moment of the Rayleigh beam is related to its classical (local) version, M^l_b, by (Kiani, 2010a, 2013; Kiani and Wang, 2012; Peddieson et al., 2003; Wang and Wang, 2007; Wang, 2005):

$$M^{nl}_b - (e_0 a)^2 M^{nl}_{b,xx} = M^l_b = -E_b I_b w_{,xx}, \tag{2}$$

where $e_0 a$ is the small-scale parameter. By mixing Eqs. (1) and (2), the nonlocal equation of motion of the system of SWCNT-nanoparticle immersed in a longitudinal magnetic field in terms of lateral deformation is derived as,

$$\begin{aligned}&\rho_b A_b \left(\ddot{w} - (e_0 a)^2 \ddot{w}_{,xx}\right) - \rho_b I_b \left(\ddot{w}_{,xx} - (e_0 a)^2 \ddot{w}_{,xxxx}\right) + M_p \left(\ddot{w}\delta(x - x_M) - (e_0 a)^2 \left(\ddot{w}\delta(x - x_M)\right)_{,xx}\right) - I_p \left(\ddot{w}_{,xx}\delta(x - x_M)\right.\\ &\left.\quad -(e_0 a)^2 \left(\ddot{w}_{,xx}\delta(x - x_M)\right)_{,xx}\right) + E_b I_b w_{,xxxx} - \eta A_b H_x^2 \left(w_{,xx} - (e_0 a)^2 w_{,xxxx}\right) = M_p g \left(\delta(x - x_M) - (e_0 a)^2 \delta_{,xx}(x - x_M)\right).\end{aligned} \tag{3}$$