International Journal of Engineering Science 107 (2016) 98–133

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

Dynamic interactions between double current-carrying nanowires immersed in a longitudinal magnetic field: Novel integro-surface energy-based models

Keivan Kiani*

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

ARTICLE INFO

Article history:
Available online 29 July 2016

Keywords:
Vibration
Double current-carrying nanowires
Magnetic field
Surface continuum-based beams
Reproducing kernel particle method (RKPM)

ABSTRACT

Transverse dynamic interactions between double current-carrying nanowires (CCNWs) immersed in a longitudinal magnetic field are of high interest. Using Biot-Savart and Lorentz laws, the approximate and exact magnetic forces exerted on the CCNWs are expressed. By employing Hamilton's principle, the equations of motion of magnetically affected CCNWs are obtained in the context of the surface elasticity theory of Gurtin-Murdoch. To this end, three approximate models as well as three exact versions of governing equations based on the Rayleigh, Timoshenko, and higher-order beam theories are developed. Via reproducing kernel particle method, the frequencies of the nanosystem are evaluated. With regard to the predicted results by the exact models, the application limits of the approximate models are displayed. Subsequently, the roles of the interwire distance, slenderness ratio, CCNWs' radius, electric current, and magnetic field strength on the fundamental frequency of the nanosystem are examined. For each of these explorations, the influences of the surface energy and shear deformation on the free dynamic response of the nanosystem are explained and discussed.

1. Introduction

Using piezoelectric materials, scientists have synthesized ensembles of vertically aligned nanowires (NWs) on a flat substrate as a nanogenerator (Qin, Wang, & Wang, 2008; Wang, Song, Liu, & Wang, 2007; Wang & Song, 2006). This advanced technology could release nanomachines from the bulk of batteries since allows harvesting mechanical energy from various environmental sources including ultrasonic waves, mechanical vibration or even blood flow. Further, the most apparent use of NWs is in electronics (Cui & Lieber, 2001; Duan, Huang, Cui, Wang, & Lieber, 2001; Hahm & Lieber, 2004). The NWs could be conductors, semiconductors or even superconductors depend on the environment's temperature and the NW's atomic structure. Due to their tiny dimensions, millions of millions transistors could be fitted on a single microprocessor and thereby, the computing speed would drastically increase. The current-carrying wires with lengths in the order of micrometers could be also exploited as precise magnetometers (Ando, Baglio, Bulsara, & Trigona, 2009; Wickenden et al., 1997, 2003). The main functions of them is to map magnetic fields which have great potential applications in space physics, biomedicine, environmental sciences, oceanography, and transportation. For most of the above-mentioned applications, groups of current-carrying NWs (CCNWs) can be used. For optimal design of such nanosystems as well as magnetically affected ones, their

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

http://dx.doi.org/10.1016/j.ijengsci.2016.07.012

free dynamic response and natural frequencies should be realized. To this end, vibration of magnetically affected double-nanowire-system as electric current carrier is aimed to be investigated via more refined models. Such a scrutiny provides a crucial step towards better understanding vibrations of more complex nanosystems, like as vertically aligned CCNWs, in the presence of a magnetic field.

The surface of solids is a very thin layer whose atom arrangements and properties are different from those of the bulk (Dingreville, Qu, & Cherkaoui, 2005; Jing et al., 2006; Miller & Shenoy, 2000). The classical continuum theory (CCT) cannot explain such a critical issue since it has been basically developed for macro-structures. By decreasing the sizes of a solid, the ratio of the surface area to the volume of the solid increases and the role of the surface effect in mechanical response of the structure becomes more important. To formulate such a vital effect, Gurtin and Murdoch (1975, 1976, 1978) proposed a novel theory to overcome the shortcomings of the CCT. In the newly developed model, the surface layer was introduced as a membrane of negligible thickness adhered to the underlying bulk without slippage. The constitutive relations of the surface layer are essentially different from those of the bulk. For an isotropic surface layer, the stresses are related to the strains through three parameters: residual surface stress, and two Lame's constants. In most of the cases, the equations of motion of the surface layer denote the nonclassical boundary conditions of the bulk. If the parameters associated with the surface layer tend to zero, the classical boundary conditions are retrieved and the size dependency is removed. Through solving the simultaneous equations of motion of the surface layer and the bulk accounting for the nonclassical conditions, the surface elasticity-based models are analyzed. To date, the surface elasticity theory of Gurtin and Murdoch (1975, 1976, 1978) has been widely applied to various problems of nanostructures such as statics (Khajeansari, Baradaran, & Yvonnet, 2012; Liu, Mei, Xia, & Zhu, 2012; Olsson & Park, 2012; Park & Klein, 2008), vibrations (Ansari, Mohammadi, Shojaei, & Sahmani, 2014; Ansari & Sahmani, 2011; Eltaher, Emam, & Mahmoud, 2012; Gheshlaghi & Hasheminejad, 2011, 2012; Hashemi & Nazemnezhad, 2013; Huang, 2008; Malekzadeh & Shojaee, 2013; Pishkenari, Afsharmanesh, & Tajaddodianfar, 2016; Wang & Feng, 2010; Yan & Jiang, 2011, 2012) and buckling (Ansari, Mohammadi, Faghih Shojaei, Gholami, & Sahmani, 2014; Li, Song, Fang, & Zhang, 2011; Park, 2012; Sahmani, Bahrami, & Aghdam, 2016; Wang & Feng, 2009; Zhang, Wang, & Adhikari, 2012) of nanobeams/nanowires as well as free vibrations (Assadi, 2013; Malekzadeh, Haghighi, & Shojaee, 2014; Wang & Wang, 2011b) and buckling (Farajpour, Dehghany, & Shahidi, 2013; Lu, Zhang, & Wang, 2011; Ravari & Shahidi, 2013; Wang & Wang, 2011a; Zhang et al., 2012) of nanoplates. In all suggested models in the present work, the equations of motion are constructed in the framework of the surface elasticity theory of Gurtin-Murdoch.

Regarding individual magnetically affected CCNWs, any cause of deflection leads to exertion of extra transverse magnetic force on the nanowire. This force corresponds to the reduction of the lateral stiffness as well as the dynamic instability of the CCNWs. In the presence of a longitudinal magnetic field, free vibration and stability (Kiani, 2014b), axial buckling (Kiani, 2015a, 2015b), forced vibration of individual CCNWs accounting for the nonlocality effect (Kiani, 2014a) have been investigated. In the case of double CCNWs (DCCNWs), the vibration of each CCNW is also influenced by the magnetic field of the neighboring CCNW (Kiani, 2015c, 2015d). Thereby, the mechanical response of the constitutive CCNWs of the nanosystem would be entirely different from that of the magnetically affected individual CCNW.

By passing electric current through doubly parallel nanowires, a magnetic field would produce around each nanowire whose characteristics are displayed by the Biot-Savart's law. Such a magnetic field plus to the longitudinally applied one correspond to the magnetic force exerted on the deformed CCNWs. By employing the Lorentz force law, the exact expressions of the above-mentioned forces are derived in the form of integro-partial differential relations. For infinite lengths CCNWs, such expressions are reduced to those simple forms which are available in the literature (Kiani, 2015c, 2015d). Such simplified formulations represent approximate version of the magnetic forces. Investigation of the capabilities of the approximate models in predicting vibration behavior of the nanosystem based on the exact formulations is one of the main goals of the present work.

This paper deals with free transverse vibrations of and dynamic interactions between DCCNWs subjected to a longitudinal magnetic field. For this purpose, the exerted magnetic force on each CCNW is evaluated based on an approximate model and an exact one. In fact, the approximate model has been basically established based on the common assumption of infinite length of the nanowires. In the newly exact model, the length of the nanowires is appropriately incorporated into the dynamic magnetic forces evaluated on the basis of the Biot-Savart law. To study transverse vibrations of the magnetically affected CCNWs and their dynamic interactions, the equations of motion are obtained according to the Rayleigh beam theory (RBT), Timoshenko beam theory (TBT), and higher-order beam theory (HOBT). In all developed models, the surface energy effect of the nanosystem is incorporated into the formulations. Based on the above-mentioned models of beams and magnetic forces, six models are developed. The approximate governing equations based on the RBT, TBT, and HOBT in order represent four, eight, and eight coupled partial differential equations (PDEs); however, those obtained using exact version of the magnetic force are inherently four, eight, and eight integro-partial differential equations (IPDEs). Finding an analytical solution to these equations is a very cumbersome job. To overcome this difficulty, the reproducing kernel particle method (RKPM) is employed to predict the free vibration behavior of the nanosystem. This efficient meshless methodology was developed by Liu, Jun, Li, Adee, and Belytschko (1995a); Liu, Jun, and Zhang (1995b) and has been widely exploited for numerical analysis of engineering and physical problems (Chen, Roque, Pan, & Button, 1998; Cheng & Liew, 2009; Ji-fa, Wen-Pu, & Yao, 2005; Kiani, 2010; Liew, Ng, & Wu, 2002; Liu, Jun, Sihling, & Hao, 1997; Nianfei, Guangyao, & Shuyao, 2009; Zhang, Wagner, & Liu, 2003). The obtained results by this method are verified with those of assumed mode method (AMM) in a particular case, and a reasonably good agreement is achieved. Thereafter, the effects of the slenderness ratio, interwire distance, CCNW's radius, magnetic field strength, and electric current on the fundamental frequency of the nanosystem are