Materials Chemistry and Physics xxx (2015) 1–11

Contents lists available at ScienceDirect

Materials Chemistry and Physics

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

Vibrations and instability of pretensioned current-carrying nanowires acted upon by a suddenly applied three-dimensional magnetic field

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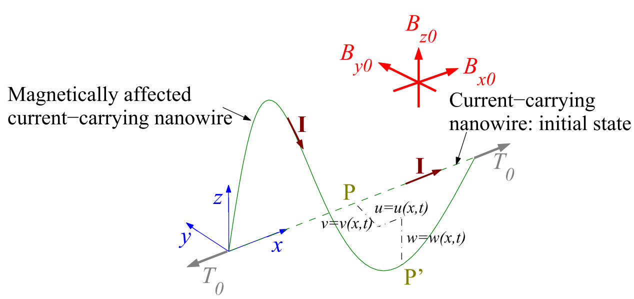
HIGHLIGHTS

- Vibrations of current-carrying nanowires in a 3D magnetic field are of interest.
- Via surface elasticity theory and Lorentz's law, governing equations are developed.
- Explicit expressions of longitudinal and transverse displacements are obtained.
- Roles of influential factors on the stability of the nanostructure are discussed.
- Effects of the components of 3D magnetic field on maximum displacements are studied.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form
24 April 2015
Accepted 30 May 2015
Available online xxx

Keywords:
Nanostructures
Computer modeling and simulation
Computational techniques
Deformation

ABSTRACT

Longitudinal and transverse vibrations of a pretensioned current-carrying nanowire subjected to a suddenly exerted three-dimensional magnetic field are of concern. Using an elastic string model by considering the surface effect, the equations of motion of the nanostructure are established. By employing admissible mode shapes and Laplace transform approach, an analytical solution is proposed to determine the nanowire's elastic field. The explicit expressions of the longitudinal and transverse displacements of the nanowire are derived. The conditions that lead to the dynamic instability of the nanostructure are also discussed. The influences of the initial tensile force, electric current, and the components of the magnetic field on the dynamic displacements are comprehensively addressed.

1. Introduction

In 1965, Moore [1,2] predicted that the number of transistors on an integrated circuit doubles approximately every two years. The so-called Moore's law is more of a self-fulfilling insight about the processors manufacturing. In order to equip a chip with more transistors, scientists must design and fabricate smaller transistors. One way to reach such a marvelous goal may be the use of appropriate ensembles of nanowires [3–5]. A nanowire is an extremely thin structure with a very high length to width ratio. It is possible to create a nanowire with a diameter of just one nanometer, although scientists commonly work with nanowires which are in the range of 30–60 nm wide. In the past two decades, there have been many interests in using carbon nanotubes as electrical carriers [6–8]. These explorations have revealed substantial

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http://dx.doi.org/10.1016/j.matchemphys.2015.05.080
0254-0584/

characteristics of current-carrying nanotubes such as Luttinger liquid behavior, ballistic conduction at room temperature, and long-extended coherent state in which potentially provide them as field effect transistors [9–11]. Due to crucial limitations of nanotubes as explained by cui et al. [12], nanowires have been proposed as a more suitable structure for carrying electrical current. In the near future, it is hoped that the vertically aligned nanowires could be exploited for fabrication of the smallest transistors, however, there are some major difficulties in the way.

When a piezoelectric-nanowire is deflected by a conductive atomic force microscopy (AFM) at the tip, the mechanical energy of deformation is converted into electricity. The performance of such an AFM-based nanogenerator will be successfully improved if an effective way can be developed that all points of the nanowire are continuously and simultaneously actuated. By applying ultrasonic waves, Wang et al. [13] tested vertically aligned ZnO nanowires to produce continuous direct-current. Such ensembles of nanowires can be used for harvesting energy and may have potential applications in powering nanodevices. Generally, such nanostructures become more dynamically unstable when they are acted upon by a magnetic field. As another example, nowadays, developing miniature magnetometers has been also increased due to their vast potential applications in oceanographic, biomedical, industrial, environmental purposes, and extraterrestrial. In magnetic gradiometers, a one-dimensional structure carries an AC current is used to measure the magnetic gradient. To study vibration of such devices, beam models or even string models can be employed according to the ratio of the flexural strain energy to the strain energy resulted from the initial tensile force. The idea of using micro-magnetometers was initiated by Wickenden et al. [14]. In thermo-vibro-mechanical analysis of these microsystems, variation of the magnetic field across the length of the string is also taken into account. With regard to many similarities between the governing equations of the problem at hand and those of micro-scaled magnetic gradiometers, the present study will be also helpful to those researchers who are interested in exploring mechanical vibrations of such tiny magnetically affected structures. For such applications, from applied mechanics point of view, the dynamic response and stability conditions of a nanowire carries an electric current in the presence of a magnetic field should be methodically realized. This paper is aimed to establish an inclusive mathematical model to answer some queries that may arise regarding the vibrations and possible instabilities of such nanoscale systems.

By passing an electric current through a nanowire, a magnetic field would produce around the nanowire that can be explained by the Biot-Savart law. On the other hand, when the current-carrying nanowire is subjected to an external magnetic field, a magnetic force (the so-called Lorentz force) is exerted on each element of the nanowire. This force is a function of the direction and amplitudes of the electric current in the deformed nanowire as well as those of the applied magnetic field. Through using the Lorentz formula, the magnetically exerted force per unit length of the current-carrying nanowire can be readily calculated. According to this formulation, not only the magnitudes of magnetic field and the electric current, but also their directions are among the major factors that influence on the vibrations of the magnetically affected current-carrying nanowires. It should be noted that controlling the direction of the electric current (which is along the tangential direction of the deformed nanowire) would not be a trouble-free job. In other words, control of the exerted magnetic force on the deformed nanowire is not as easy as it may be thought. As it will be shown, such a force also corresponds to the initiation of dynamic instability within the nanostructure under particular conditions. As a result, realizing the factors affecting instability and vibrations of the nanowire is of great importance. This information would help scientists and engineers to design and construct more stable nanowires' systems to undertake the considered tasks more efficiently.

Experiments show that the effective elastic properties of nanowires are size-dependent [15–18]. Additionally, other theoretical evidences support this fact that the mechanical behaviors of nanowires are basically size-dependent [19–22]. Such a size-dependency plays a vital role in overall performance of nanowires and cannot be explained by the classical continuum theory (CCT) at all. On the other hand, for atomic modeling of such nanostructures, many atoms should be taken into account since the lengths of nanowires are generally in the order of micrometer. It indicates that application of atomistic-based approaches for dynamic analysis of nanowires takes a lot of labor and time costs, and therefore, it would not be a reasonable way. To overcome the drawbacks of the CCT and to reduce the costs of the atomic approaches, several size-dependent theories have been developed since the past century. The surface elasticity theory of Gurtin-Murdoch [23,24] is one of the most popular size-dependent theories that the surface energy of the nanostructure is incorporated into its total energy. This advanced theory of elasticity explains that when the surface-to-volume ratio of the nanostructure increases, the effect of the surface energy on deformation becomes highlighted. To this end, the surface's atoms are modeled by a layer with negligible thickness whose elastic properties and residual surface stress should be appropriately determined. The constitutive relations of this layer are also completely different from those of the bulk matter. Since the past decade, the surface elasticity theory of Gurtin-Murdoch [23,24] has received increasing attentions to examine mechanical problems associated with nanostructures [25–32].

To date, nonlocal continuum theory of Eringen [33–35], surface elasticity theory of Gurtin-Murdoch [23,24] or a combination of them has been employed for analyzing a wide range of the problems in applied mechanics that the nanostructure can be simulated by a rod, beam, plate, or shell. We focus more specifically on the problems pertinent to the nanowires and nanotubes. A brief review of the literature shows that bending and resonance behavior of nanowires [36–38], free vibrations of nanowires [39–42] and nanotubes [26,43–45], forced vibrations of nanowires [46,47] and nanotubes [48–50], wave propagation within nanowires [51–53] and nanotubes [54–56], nanofluidic–nanotube interactions [57–60], moving nanoparticle–nanotube interactions [61–65], various buckling aspects of nanotubes [66–69] and axial buckling of nanowires [70–73], vibrations of magnetically affected nanotubes [74–76] and nanowires [77,78] have been examined in some detail. Recently, free and forced vibrations of a single nanowire as well as free vibrations of double current-carrying nanowires in the presence of a longitudinal magnetic field have been explored [79–81]. Nevertheless, vibrations and instabilities of current-carrying nanowires immersed in a three-dimensional magnetic field have not been studied carefully. To bridge this scientific gap, herein, we implement the surface elasticity theory for dynamic analysis of the magnetically affected current-carrying nanowires. Since such nanostructures are generally so long and their lateral vibrations are of interest, therefore, their flexural rigidity can be ignored and an appropriate string model would be satisfactory for our purpose. Surely, when the length to diameter ratio of the nanostructure is lower than a specific level, beam models would provide more reasonable results with respect to the present string model. The study of vibrations of current-carrying short nanowires subjected to a general magnetic field could be considered as a hot topic for future works.

In this study, longitudinal and transverse vibrations of a current-carrying nanowire subjected to a three-dimensional magnetic field

Please cite this article in press as: K. Kiani, Vibrations and instability of pretensioned current-carrying nanowires acted upon by a suddenly applied three-dimensional magnetic field, Materials Chemistry and Physics (2015), http://dx.doi.org/10.1016/j.matchemphys.2015.05.080