Physica E: Low-dimensional Systems and Nanostructures 97 (2018) 191–205

Contents lists available at ScienceDirect

Physica E: Low-dimensional Systems and Nanostructures

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

Spatial buckling analysis of current-carrying nanowires in the presence of a longitudinal magnetic field accounting for both surface and nonlocal effects

Shahin Foroutan, Amin Haghshenas, Mohammad Hashemian, S. Ali Eftekhari, Davood Toghraie *

Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran

A R T I C L E I N F O

Keywords:
Nanostructure
Metal
Buckling analysis
Eringen's nonlocal theory

A B S T R A C T

In this paper, three-dimensional buckling behavior of nanowires was investigated based on Eringen's Nonlocal Elasticity Theory. The electric current-carrying nanowires were affected by a longitudinal magnetic field based upon the Lorentz force. The nanowires (NWs) were modeled based on Timoshenko beam theory and the Gurtin-Murdoch's surface elasticity theory. Generalized Differential Quadrature (GDQ) method was used to solve the governing equations of the NWs. Two sets of boundary conditions namely simple-simple and clamped-clamped were applied and the obtained results were discussed. Results demonstrated the effect of electric current, magnetic field, small-scale parameter, slenderness ratio, and nanowires diameter on the critical compressive buckling load of nanowires. As a key result, increasing the small-scale parameter decreased the critical load. By the same token, increasing the electric current, magnetic field, and slenderness ratio resulted in a decrease in the critical load. As the slenderness ratio increased, the effect of nonlocal theory decreased. In contrast, by expanding the NWs diameter, the nonlocal effect increased. Moreover, in the present article, the critical values of the magnetic field of strength and slenderness ratio were revealed, and the roles of the magnetic field, slenderness ratio, and NWs diameter on higher buckling loads were discussed.

1. Introduction

Nanotechnology is an important issue, since diminishing the particles of a matter in the nano-order increases the number of atoms existing on the substance surface. In addition, in the nano-order, the quantum principles governing the material trait are different from the classical principles governing our surroundings. These discrepancies cause a profound alteration in the mechanical feature of the nanostructure. In 1959, Richard Feynman first presented the idea of nanotechnology in his speech, “There's plenty of room at the bottom” [1]. In 1974, the term “nanotechnology” was first used by Norio Taniguchi to describe the process of manufacturing controllable precise material in order of a nanometer. NWs offer a variety of applications in different fields of studies. The application of NWs and nanofluidics in electronics and optoelectronics, electromechanical systems, and energy scavenging has been investigated for many years [2–14].

Park studied the critical buckling strain of silicon NWs, and the impact of surface stresses was imposed. The buckling of silicon NWs was under axial compressive load. The calculations in this work were done using nonlinear finite element [15]. Chiu and Chen investigated the buckling behavior of NWs under axial compressive load based on the Kirchhoff Love Assumption. In order to demonstrate the surface stress effect on the critical buckling of the NWs, diverse degrees of surface stresses were accounted [16]. Khater et al. investigated the effect of surface energy and thermal loading on the buckling analysis of NWs using the Euler-Bernoulli Beam and Gurtin-Murdoch theories [17].

Gao et al. researched into buckling analysis of NWs on elastomeric substrate, and enforcing the surface effect. In their research, they identified that the buckling behavior of NWs was extremely influenced by surface effects [18]. Hu researched into the buckling and vibration behavior of NWs by considering the Surface Elasticity Theory [19]. Kiani studied the axial buckling of doubly parallel slender NWs carrying electric current and immersing in magnetic field. In this study, each NW was affected with another NW magnetic field in addition to its own magnetic field. The Euler-Bernoulli and Surface Elasticity theories were used to drive the governing equations. The conclusions were based on the effect of slender ratio, electric current, magnetic field, and inter-wire distance on the buckling behavior of NWs. The main result of this study was summarized in the effect of inter-wire distance, demonstrating the increase in this parameter accompanied by an increase in the critical

* Corresponding author.
E-mail address: Toghraee@iaukhsh.ac.ir (D. Toghraie).

https://doi.org/10.1016/j.physe.2017.11.015
Received 29 April 2017; Received in revised form 5 November 2017; Accepted 17 November 2017
Available online 21 November 2017

buckling load [20]. Jiang and Yan explored the elastic behavior of bending NWs using the Timoshenko Beam Theory considering the surface effects. With different boundary conditions, the clear solution was derived to investigate the effect of residual surface stress, surface elasticity, and shear deformation on the stiffness and Young's modulus [21]. Chiu and Chen explored the bending and resonance behavior of NWs based on the Timoshenko Beam Theory. They considered a high-order surface stress model incorporating into continuum mechanics. Results presented the deflection curves, rotation angle for bending, maximum deflection, and resonance frequency followed by comparing them with the classical models of the Euler-Bernoulli beam [22]. Ansari et al. investigated the vibration behavior of piezoelectric nanobeams in the vicinity of post-buckling using the Timoshenko Beam and Nonlocal Elasticity theories. In the investigation, piezoelectric nanobeams were affected by an axial load, applied voltages, and uniform temperature alteration. Results of this work include the natural frequency of piezoelectric nanobeams in the vicinity of post-buckling [23].

The surface elasticity theory was first proposed by Gurtin and Murdoch to apply the surface effect of a material [24,25]. On nano and micro scales, the surface of a structure is a considerable amount in comparison to its bulk zone. Therefore, a variety of mechanical parameters can be defined for the surface structure. In this theory, mechanical behavior of material surfaces, and the relation between materials and bodies which stick to material surfaces were investigated. This theory has been applied in various studies including bending and buckling analysis [26,27], and vibration behavior of mechanical structures [28,29]. Rouhi et al. investigated the effect of surface elasticity theory on nanoscale cylindrical shells. The equations of motion comprising the effect of surface stress were gained based on the First-Order Shear Deformation Theory and using the Hamilton's Principle. The results represented the size-dependent vibration behavior of nanoshells imposing various boundary conditions [30]. Juntarasaid et al. analyzed the buckling and bending behavior of NWs due to uniformly distributed load considering various boundary conditions. The effect of surface elasticity accompanied by nonlocal elasticity theory was investigated. Results indicate a direct relationship between the surface stress and the Elasticity Theory with displacement and buckling load [31]. Yao and Chen probed into the effect of the surface elasticity theory on the bending of NWs. In this study, a new elastic theory was implemented for nanomaterials, indicating merely the bulk surface-energy density and the surface relaxation parameter involved as two autonomous parameters to characterize the surface effect [32]. Kiani investigated the vibration and instability of current-carrying NWs immersed in a longitudinal magnetic field considering surface effects. In this regard, results mainly showed the effect of magnetic field, electric current, and initial tensile force [33–35]. Kiani also studied the vibration and instability of double current-carrying NWs systems acting upon a longitudinal magnetic field using the Biot-Savart Law and surface elasticity theory [36,37]. Additionally, Kiani examined the axial buckling behavior of doubly parallel current-carrying NWs affected by a longitudinal magnetic field using Timoshenko beam accounting for surface elasticity approach [38].

The nonlocal elasticity theory was first established by Eringen [39–42]. In order to study materials on nanoscale, the classical theories fail to make an accurate prediction. Therefore, the nonlocal elastic theory is used. According to this theory, stress field at a point depends on the strain field at all points in addition to its strain field. The Eringen's theory has been used to investigate the vibration and wave propagation of nanotubes [43–46], fracture and dislocation mechanics [47–49], buckling and bending analysis [50–53]. Eltaher et al. researched into the buckling and bending behavior of functionally graded (FG) nanobeams using the nonlocal elasticity theory so that material properties were presumed to vary through the thickness of nanobeams. Results indicated the profound effect of material distribution profile, boundary condition, size-dependence, and neutral axis position on the bending and buckling behavior of nanobeams [54].

This investigation is based on the Timoshenko beam theory, Gurtin-Murdoch surface elasticity theory, and Eringen's nonlocal elasticity theory. To evaluate the governing equation, an efficient differential quadrature method is applied, and a proper method is used to apply the two sets of boundary conditions: simple-simple and clamped-clamped. The previous study [55] considered merely the surface effect, and ignored the nonlocal theory. Thus far, to the best of the author's knowledge, no investigation has been conducted to study NWs buckling behavior based on the surface and nonlocal elasticity theories considering magnetic field and electric current in a 3D position. Finally, results are compared with those reported in Ref. [55], and discussed thoroughly.

2. Definition of the problem

Fig. 1 displays a buckled NW under axial load. The NW carrying electric current, I_0, is affected by a longitudinal magnetic field, B_0. The diameter and length of NW are D_0 and l_b, respectively, and described in a Cartesian coordinate system. Direction x designates the axis of NW, while y and z directions are perpendicular to NW. In addition, transverse displacements are defined in y and z directions. The studied NW can be considered a simply-supported beam. The main purpose of this investigation is to determine the critical buckling load of the described NW using the Timoshenko Beam, Gurtin-Murdoch, and Eringen's Nonlocal theories.

3. Governing equations

In order to derive the governing equations, the Timoshenko Beam Theory is utilized. The following equations of the Timoshenko Beam Theory are one-dimensional. However, the investigated equations are three-dimensional.

$$\frac{\partial Q}{\partial x} + q - \frac{\partial}{\partial x}\left(N\frac{\partial w}{\partial x}\right) = 0, \tag{1a}$$

$$\frac{\partial M}{\partial x} - Q = 0, \tag{1b}$$

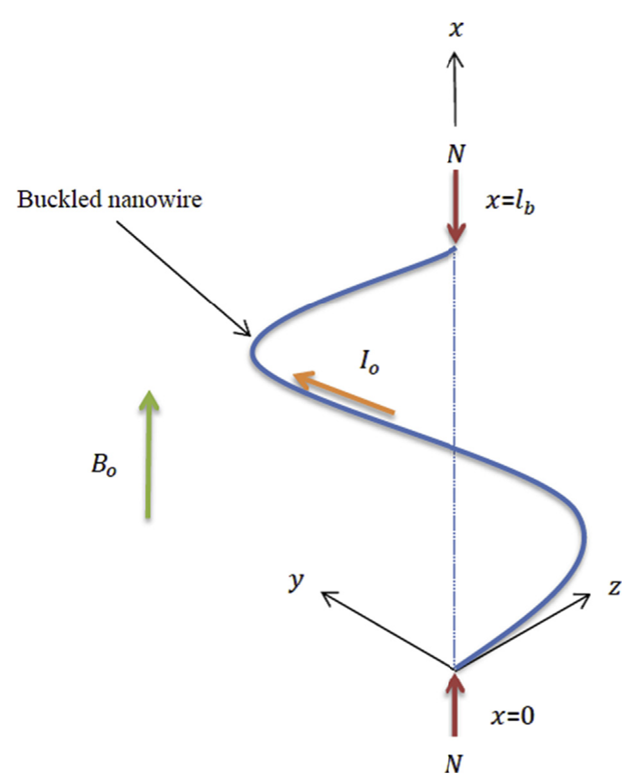

Fig. 1. Buckled NW immersed in magnetic field by an axial load.