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Column buckling of magnetically affected stocky nanowires carrying electric current

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Axial load-bearing capacity of current carrying nanowires (CCNWs) acted upon by a longitudinal magnetic field is of high interest. By adopting Gurtin–Murdoch surface elasticity theory, the governing equations of the nanostructure are constructed based on the Timoshenko and higher-order beam models. To solve these equations for critical compressive load, a meshfree approach is exploited and the weak formulations for the proposed models are obtained. The predicted buckling loads are compared with those of assume mode method and a remarkable confirmation is reported. The role of influential factors on buckling load of the nanostructure is carefully addressed and discussed. The obtained results reveal that the surface energy effect becomes important in buckling behavior of slender CCNWs, particularly for high electric currents and magnetic field strengths. For higher electric currents, relative discrepancies between the results of Timoshenko and higher-order beam models increase with a higher rate as the slenderness ratio magnifies.

1. Introduction

Assessing electrical transport in metallic nanowires (NWs) gives brilliant opportunities to profound studies and practical applications in electronics [1–3], energy harvesting [4,5], optoelectronics [6,7], and nanoelectromechanical systems (NEMS) [8–10]. Due to the special functionalities of some nanodevices, a magnetic field may be applied to ensembles of NWs carrying electric currents to control their vibrations. Exploring the axial load-bearing capacity of such nanosystems is a crucial task for better realizing of their mechanical behavior. As a basic step towards such a goal, axial buckling behavior of an individual current carrying NW (CCNW) should be carefully explored.

To realize the mechanical behavior of nanostructures, atomistic-based models are among those that lead to the most accurate results, however, high labor and time costs limit their exploitations. As an alternative approach, several advanced continuum theories have been developed in the past century, including micropolar continuum theory of Cossearts [11], couple stress theory of Toupin and Mindlin [12–15], strain gradient theory of Aifantis [16,17], nonlocal continuum theory of Eringen [18–20], and surface elasticity theory of Gurtin and Murdoch [21,22]. The main privilege of these novel theories with respect to the traditional theory of elasticity is the incorporation of the size or surface effect parameters into the equations of motion. The latterly above-mentioned theory explains that the solid body consists of surface layer and bulk material. The surface layer is regarded as a deformable medium of zero thickness that covers the bulk zone and has been tightly bonded to that. The governing equations of the bulk zone are identical to those of the traditional theory of elasticity of the body. However, those of the surface layer have been totally modified based on the concept of zero thickness. In addition, the constitutive relations of the surface zone are methodically established according to the concepts of surface residual tension, continuity of the displacements at the interface of the surface layer and the bulk material, and elastic constants of the surface zone, the so-called Lame's constants of the surface layer. The magnitudes of the parameters pertinent to the surface zone are commonly determined by comparison of the obtained results from the surface elasticity model and those of an appropriate atomistic-based approach [23,24]. In nano-scaled structures, the ratio of the surface area to the bulk volume becomes large enough that the surface effect cannot be ignored at all. In other words, the share of the surface strain energy in the total strain energy becomes significant and such effect should be appropriately taken into account.

To date, various advanced theories of elasticity have been exploited in continuum-based modeling of the problems associated with the beam-like nanostructures. For instance, vibrations [25–28], nonlinear dynamics [29–32], dynamic instability due to movement [33,34], magneto-elasto-dynamics [35–39], and buckling [40–42] of nanotubes have been widely studied via nonlocal continuum theory of Eringen. Additionally, buckling [43–49], vibrations [50–55], and statics [56–58] of NWs have been investigated in the context of the surface elasticity theory of Gurtin

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and Murdoch. Concerning magnetically affected CCNWs, their free and forced vibrations [59,60] and their dynamic interactions in the case of doubly parallel lengthy CCNWs [61] using the surface elasticity theory have been examined and a brief knowledge regarding them has been beginning to come out. However, the axial buckling behavior of these tiny structures has not been addressed yet. Given the importance of the issue, in this paper we deal with axial buckling of CCNWs in the presence of a longitudinal magnetic field. In the previous works, the CCNWs were assumed to be lengthy enough that the string's model would be satisfactory in modeling of their vibrations. However, to study wave propagation and buckling analysis of these nanostructures, the flexural and shear deformations could also play a crucial role depending on the length to diameter ratio. This work is devoted to buckling study of magnetically affected stocky CCNWs (i.e., nanostructures with slenderness ratios lower than a particular level) and special attentions should be paid to the shear deformation effects. To this end, appropriate shear deformable beam theories should be implemented.

The obtained governing equations for the problem are difficult to solve analytically. It is chiefly related to the coupled terms of Lorentz's force that transversely act on the CCNWs immersed in a longitudinal magnetic field. Due to the appearance of such forces on the nanostructure, not only the size of the equations of motion increases by two, but also some complexities are arrive at solving them. As an alternative solution, reproducing kernel particle method (RKPM) is used for buckling analysis. This method is initiated by W.K. Liu and his coworkers [62–64] which is now known as one of the most efficient and powerful methods in the meshfree family. It is worth mentioning that the continuity of RKPM's shape functions is commonly higher than the continuity of FEM's shape functions. In contrast to the FEM whose shape functions have the Kronecker delta property, the shape functions of RKPM do not meet such an identity. This fact leads to some difficulties in enforcing the essential boundary conditions and special treatments should be considered. Herein, corrected collocation method [65] is implemented that ensures us regarding the exact satisfaction of the essential conditions. Through application of this method, the stability of the numerical model is not violated by an increase of the number of particles and a higher convergence rate is commonly achieved in compared to the traditional collocation method.

Herein, by using Lorentz magnetic force, the governing equations in terms of transverse displacements are constructed based on the Timoshenko and higher-order beam theories accounting for the surface energy effect. The weak formulations of the problem are then derived via Galerkin approach in conjunction with an efficient meshfree method. In a particular case, the obtained results are verified with those of another numerical method, and a reasonably good agreement is achieved. Subsequently, the effects of electric current, strength of magnetic field, slenderness ratio, nanowire's diameter, and surface energy effect on the critical compressive load of the nanostructure are comprehensively examined. The obtained results can be regarded as a pivotal step towards buckling analysis of more complex nanosystems such as vertically aligned nanowires carrying electric current which are expected to be the building blocks of the future NEMS.

2. Definition of the problem

Consider a finite length current-carrying nanowire in the presence of a longitudinal magnetic field as shown in Fig. 1. The nanowire's length and diameter are l_b and D_0, respectively, and a constant current I_0 passes through the nanowire which immersed in a longitudinal magnetic field of strength, B_0. The mechanical interaction of the nanowire with its surrounding medium has been ignored since the author's primary concern is to examine the effects of electric current and strength of the applied magnetic field on the buckling behavior of magnetically affected CCNWs. Such interactions can be appropriately modeled by continuous transverse and rotational springs and have been widely studied for vibrations and buckling analysis of embedded nanowires and nanotubes. Based on Lorentz's formula, it can be shown that the exerted magnetic force on the transversely deformed nanowire in the context of small deformation are evaluated by [59,60] $f_{my}^{[\cdot]} = B_0 I_0 \frac{dw^{[\cdot]}}{dx}$ and $f_{mz}^{[\cdot]} = -B_0 I_0 \frac{dv^{[\cdot]}}{dx}$, which in order represent the components of Lorentz's force along the y and z axes, $\frac{d[\cdot]}{dx}$ denotes the first derivative of $[\cdot]$ with respect to x, $v^{[\cdot]} = v^{[\cdot]}(x)$ and $w^{[\cdot]} = w^{[\cdot]}(x)$; $[\cdot] = T$ or H in order are the deflections of the nanowire along the y or z axis. Throughout the paper, the parameters of the nanowire which are modeled based on the Timoshenko and higher-order beam theories have been denoted by the superscripts T and H, respectively. The nanowire is also subjected to an axial compressive load of magnitude N. The primary objective of this study is to determine the buckling load of such a nanostructure by using shear deformable beam theories accounting for surface effect.

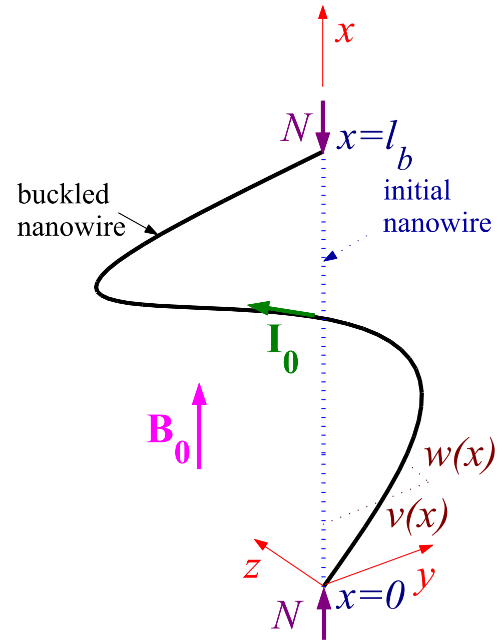

Fig. 1. Magnetically affected nanowire carrying current acted upon by an axial load.

To this end, the explicit governing equations of the problem based on the Timoshenko beam theory (TBT) and higher-order beam theory (HOBT) are derived. Subsequently, an efficient meshfree methodology is employed and the axial load corresponds to the buckling of the nanostructure is calculated. Finally, the roles of the surface energy, slenderness ratio, and NW's radius on the axial buckling behavior of the nanosystem are examined.

3. Axial buckling behaviour of the CCNWs using various beam theories

3.1. Assessment of buckling using TBT accounting for the surface energy

3.1.1. Governing equations

The governing equations of a magnetically affected nanowire carrying electric current using TBT accounting for the surface energy are written as follows: