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Pull-in analysis of an electrostatically actuated nano-cantilever beam with nonlinearity in curvature and inertia

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ABSTRACT

In this paper, the nonlinear behavior of electrostatically actuated carbon nanotubes (CNTs) is investigated based on a comprehensive model with nonlinearity in curvature, inertia and electrostatic force. The aim of this study is to show when the nonlinear formulation needs to be taken into account and when the linear formulation can simulate the system behavior accurately. The model comprises a cantilevered CNT suspended over a fixed electrode plate from which a DC potential difference is imposed. A relatively large gap between the CNT and the ground plate is considered. The versatile Galerkin method is employed to reduce the nonlinear integro-differential equations of motion to a set of nonlinear ordinary differential equations in time, and then, the reduced equations are solved by direct numerical integration. Dynamic response of the system before and beyond the pull-in voltages and effect of gap to length ratio of the CNT are studied. It is shown that in a large gap to length ratio, when the applied voltage is close to the corresponding pull-in voltage the nonlinear terms have a profound role in the dynamic behavior of the system. Eventually, the contribution of nonlinear terms are examined and it is found that the nonlinear inertia and curvature terms have softening and hardening effects, respectively, whereas the hardening effect of the nonlinear curvature has a major contribution.

1. Introduction

Carbon nanotubes are used as new materials in the fields of nano-technology, molecular-scale engineering and quantum technology. They exhibit superior electronics and mechanical properties. The terapascal range of Young's modulus [1,2] and the capability of sustaining high strains without fracture [3] make them the strongest material known today. Because of the superior properties of carbon nanotubes (CNTs), they play a major role as functional components in nano-material and nano-electromechanical systems (NEMS). Recently, various atomistic-based techniques, such as molecular dynamics (MD) simulations, have been employed to model the dynamic behavior of the nanotubes [4,5]. However, continuum-based elasticity models have also been extensively used to model nano-mechanics, structural deformation and stability, vibration, and heat transfer. The result of continuum-based modeling agrees well with many results obtained from atomistic-based studies and experiments. These close agreements show that continuum-based modeling could be employed in the nano-scale area. For instance, the Euler–Bernoulli beam theory has been employed to investigate the nanotubes structural instability such as column buckling [6], static deflection [7], sound wave propagation [8], resonant frequency and vibrational modes [9,10] vibration of multi-wall carbon nanotubes [11,12], nonlinear vibration [13] and flow induced structural instability [14]. CNTs under electrostatic loads have been analyzed using continuum-based modeling [15,16]. The results have been compared to experimental results [17] and also molecular dynamic results [4,5], which show good agreements. Some NEMS devices such as relays [18–20], tweezers [21,22], switches [4,5,23–25], random access memory [26–28] and torsional actuators [29] emerge by means of electrostatic actuation. AC and/or DC electrostatic actuation as a versatile method is also employed to excite micro-electromechanical systems (MEMS) [30–37]. By applying the potential difference between the CNT and the electrode, the beam bends and approaches the electrode plate and the elastic force tends to return the nanotube back into the undeformed position. Exceeding the applied voltage to a certain value would cause the CNT collapse onto the electrode in which the associated applied voltage is called pull-in voltage.

In previous works [4,16] a good agreement between linear and nonlinear formulation was reported, whereas the gap–length ratio in the considered test case in these works were less than 0.25. On the other hand, large deflection of CNT due to high gap–length ratio is reported based on MD simulation [24]. In some applications, where a large displacement of the cantilever is required, employing the high gap–length ratio is recommended. In this situation, the geometric nonlinearity due to the nonlinear strain relation and nonlinear curvature may find a more prominent role in dynamic behavior of the system. The question is in which electrostatic gap to

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