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Pull-in instability of carbon nanotube-reinforced nano-switches considering scale, surface and thermal effects

W.D. Yang, X. Wang*, C.Q. Fang

School of Naval Architecture, Ocean and Civil Engineering (State Key Laboratory of Ocean Engineering), Shanghai Jiao Tong University, Shanghai 200240, PR China

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ABSTRACT

In this paper, an analytical method is presented to investigate the effect of surface characteristic and temperature change on the pull-in instability of electrically actuated nano-switches reinforced by carbon nanotubes (CNTs) based on Eringen's nonlocal beam theory. An extremely nonlinear fourth-order governing equation for the doubly clamped nano-switches made of CNTs/Si composites nanobeam is derived and solved by using the principle of virtual work, where Van der Waals force as atomic interactions and Casimir force as macro effects of quantum field fluctuation of vacuum are combined as an electrostatic force with fringing field effects. The results show that both the pull-in voltage and pull-in deflection of CNTs/Si composite nanobeam increase with the increase of CNTs volume ratio but decrease with the increase of temperature change. The coupling influences of small scale parameter, geometric behavior, surface characteristic and thermal effect on the pull-in instability of electrostatically actuated CNTs/Si nanobeam are detailedly discussed.

1. Introduction

More and more interests are attracted in the Micro/Nano electromechanical systems (MEMS/NEMS) due to their potential application in biosensors, information technology, aerospace, automotive systems and transportation [1,2]. In recent years, the nanostructures and nanosystems have been utilized in the biosensor and medicine, like DNA or RNA analysis [3,4], proteins and nucleic acids diagnostics [5] and poisonous gas detection [6]. Consequently, the relevant important applications lead to the significant technologies in communication systems and nanoscale devices. Therefore, numerous electrostatically actuated NEMS devices, such as nano-switches [7], nano-tweezers [8], random access memory [9] and super-sensitive sensors [10], are widely studied, designed, fabricated and evaluated.

Generally, the electrostatically actuated NEMS devices are designed as a typical conductive nanobeam-type actuator suspending over a substrate. When an electric potential difference between the actuator and the substrate has been applied, a particular deflection of the nanobeam occurs and the gap between them decreases to a correspondent value. If the applied electric potential difference gradually increases and exceeds a certain potential, the nanobeam would become unstable and collapse onto the substrate. Moreover, in nanoscale, the molecular interaction like van der Waals force and Casimir force present a significant contribution to the attraction between the nanobeam and the substrate [11,12]. Herein, the critical electric potential which causes the nanobeam to collapse onto the substrate is called the pull-in voltage and the correspondent maximum deflection of the structure before failure is called the pull-in deflection [13]. Both of two parameters are important to evaluate the stability and safety of the actuator.

There have been a lot of studies on the static and dynamic pull-in instability of micro- and nano-actuators. A distributed parameter model was proposed to analyze a cantilever type nanoscale actuators compared to the lumped parameter model and gave an analytical solution of nonlinear governing equation by using the Green's function [11,14,15]. They found that the lumped parameter model underestimate the pull-in parameters of the nanoactuators. Lin and Zhao studied and compared three different theoretical models, namely 1D lumped model, linear supposition model and the planar model [16]. They found that when the pull-in phenomenon is featured as a strong nonlinear problem, the linear superposition could provide a more accurate solution for the design.

* Corresponding author.
E-mail address: xwang@sjtu.edu.cn (X. Wang).

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However, the planar model should be utilized when the dynamical behavior of MEMS switches is studied. The pull-in instability of an electrostatically actuated micro-cantilever beam was investigated by using a large deflection model [17]. For large gap separations, coupled effects of geometric nonlinearity, and nonlinear electrostatic forces with higher order correction terms could cause deviation from the linearized result. They found that the predicted results would be much improved if higher order terms of nonlinearity are taken into account during static and dynamic analysis. Yang et al. proposed a linear distributed load model to study the pull-in instability of nano-switches with electrostatic force and intermolecular force, and then gave the closed-form solutions [18].

Additionally, the supported boundary condition has important influence on the design and fabrication of micro-/nano-scale devices for various applications. The cantilever-type nano-sensors/actuators have been widely fabricated as atomic force microscopy (AFM) due to the super-high sensitivity and flexibility of cantilever structure [19,20]. Whereas, the doubly-clamped-type MEMS/NEMS have also been fabricated to be variety of nano-actuators/switches like RF switches, point-mass molecular and toxic gas sensors [21].

Because thermal effects have significant influences on the stability and working performance of nanoscale electromechanical materials and structures, the influence of temperature change on the pull-in instability of functionally graded material microbeams is described in Ref. [22]. The effect of temperature change on the pull-in voltage and natural frequency of an electrostatically actuated microplate is presented in Ref. [23]. The effect of DC voltage and temperature change on the mechanical behavior of functionally graded material micro-tweezers is studied in Ref. [24]. However, they do not consider the scale and surface effects in above analytical models and thus the results cannot reflect the size-dependent property of nanoscale material and structures.

Generally, the scale effect of nanostructure is compatible with the size of molecular and/or atomic interactions, in which the long range forces between atoms should be considered. To consider the scale effect on the physical problem of micro and nano-structures, Eringen and Edelen found the theory of non-local continuum mechanics containing information about the long-range forces between atoms by introducing the internal length scale into the constitutive equations as a material parameter [25]. Mehdipour et al. investigated the resonant frequency, dynamic pull-in voltage of SWCNT mass sensor based on nonlocal Euler-Bernoulli beam theory [26]. They aimed to study the sensitivity of the cantilevered SWCNT to the values and positions of attached mass. They found that the mass sensitivity is soared notably by considering nonlocal elasticity parameters. The static pull-in instability of nano-cantilever beam immersed in a liquid electrolyte was studied in Ref. [27]. They found that the van der Waals force and size effect influence the pull-in parameters based on modified Adomian decomposition (MAD). The size effect largely influences the beam deflection and is more significant for small thickness. Also, the deflection of nanobeam is overestimated without considering size effect.

The interest to the model of surface elasticity by Gurtin and Murdoch grows fast with respect to development of nanotechnology [28]. Surface effect has become more and more important in analyzing the size-dependent characteristics of nanoscale structures due to that the volume ratio of surface region to bulk increases. Malekzadeh and Shojaee analyzed the surface and nonlocal effects on the nonlinear flexural free vibrations of non-uniform cross section nanobeams [29]. They found that the increase of the amplitude ratio caused reduction of the surface effects and the effects of surface elasticity and initial stress decline with the increase of the width taper ratio. Eltaher et al. investigated the coupled effect of surface properties and nonlocal elasticity on vibration characteristics of nanobeam based on finite element method (FEM) [30]. They found that in the nano regime, the nonlocal effect tends to decrease the fundamental frequency as the beam thickness decrease. Whereas, the surface effects increase the fundamental frequency as the thickness decrease, which they have opposite effects on the material set.

Recently, carbon nanotubes as one of promising reinforcements have been widely studied for improving static and dynamic mechanical properties of their composite materials [31]. It is interesting that carbon nanotubes reinforced silicon (CNTs/Si) composite nanobeam are selected to design a nano-switch in various nano-apparatus. To authors' knowledge, theoretical study for the influence of thermal effects on the pull-in instability characteristics of nanoscale composite electrostatic switches is few so far. Therefore, it is significant to investigate environmental temperature change on pull-in instability of carbon nanotube-reinforced nano-switches considering scale and surface effects further.

It should be noted that the content and results in the previous work presented by authors [32]are mainly to study the electro-mechanical coupling properties of carbon nanotubes (CNTs) reinforced nano-actuators with cantilever-type supported condition no-considering thermal effect. The present work aims to investigate the coupling influences of thermal effect, CNTs volume ratio, scale-dependent effect and surface effect on the pull-in instability of CNTs/Si composite nano-switch with two clamped ends, subjected to the electrostatic force with fringing field effects as van der Waals interactions and Casimir force. Herein, the small scale effect is described by the Eringen's nonlocal elasticity theory containing the long-range forces among atoms and the surface effects consist of the surface modulus and surface residual stress based on the Young–Laplace equation. Moreover, van der Waals force is generally considered when the distance is shorter than 20 nm whereas Casimir force as the macro attractive interaction from the fluctuation of quantum field when the distance is larger than 20 nm [14]. By deriving and solving one extremely nonlinear fourth-order govern equation, the influences of temperature change, CNTs volume ratio, small scale behavior, surface effect, van der Waals interaction and Casimir force are parametrically discussed in details. The results may provide a useful reference for understanding the main role in the pull-in instability property of electrostatically actuated CNTs/Si switches.

2. Model and nonlinear govern equation

Fig. 1 illustrates a CNTs/Si nano-switch with two clamped ends, under electrostatic and thermal loads, where van der Waals force and Casimir force are also considered in the applied force exerting on the CNTs/Si nanobeam. The CNTs/Si composite nano-switch is modeled by n-doped silicon substrate and CNTs reinforced thin beam of length L, width w and thickness h. The initial gap between CNTs/Si composite beam and n-doped silicon substrate surface is g. The coordinate system is fixed to the neutral axis at the left end of nanobeam where x and z refer to the horizontal and vertical direction, respectively.

2.1. The mechanical and thermal behavior of CNTs reinforced-composite

The CNTs reinforced nanobeam is made of a mixture of CNTs and silicon matrix by some certain volume ratio, as shown in Fig. 2. For the bulk of nanobeam, the dispersion of CNTs is assumed to be uniformly distributed in the composite and the composite is considered as isotropic. Considering the surface layer of CNTs reinforced composites, CNTs are bonded with the bulk and no CNTs