Sensors and Actuators A 220 (2014) 178–187

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Electromechanical coupling characteristics of carbon nanotube reinforced cantilever nano-actuator

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ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form
26 September 2014
Accepted 9 October 2014
Available online 22 October 2014

Keywords:
Carbon nanotube reinforced composites
Pull-in instability
Casimir effect
Nonlocal elasticity
Freestanding behavior

ABSTRACT

The electromechanical coupling characteristics of carbon nanotubes (CNTs) reinforced cantilever nano-actuator are investigated by considering surface effect, nonlocal scale effect containing the long-range forces among atoms, van der Waals force as molecular interaction, and Casimir force as macro effect of quantum field fluctuation. The extremely nonlinear governing equation is derived by utilizing energy methods based on Eringen's nonlocal elasticity theory and Young–Laplace's surface effect model. Some useful finding and results show that the pull-in voltage and deflection of nano-actuator increase with the increase of CNTs volume ratio, the increase of the nonlocal scale parameter enhances the pull-in voltage, but declines the pull-in deflection, and the surface effect becomes gradually significant as the thickness of CNTs reinforced nano-actuator decreases. In addition, it is found that van der Waals force and Casimir force could lead to the collapse of nano-actuator without applied voltage, where the influence of Casimir force is more significant than that of van der Waals force on the electromechanical coupling behavior of CNTs reinforced nano-actuator.

1. Introduction

Because nano-electromechanical systems (NEMS) appear in lower energy consumption and better electromechanical characteristics [1,2], they have been increasingly used in engineering applications such as nano-switches [3,4], nano-tweezers [5], super-sensitive sensors and actuators [6].

NEMS are generally modeled to be a typical conductive nanobeam-type suspending over a substrate [7–14]. Quantum cantilever actuators are designed to control the nanoscale gap for tuning the electron states between the two surfaces under the applied voltage, where the gap between two surfaces under actuation can be tuned over a maximum range of 55 nm with an applied voltage of 60 V [15]. Apart from these, there are lots of nano-cantilever actuators and sensors fabricated by various nanoribbons/nanowires [16,17]. When the typical conductive nanobeam is subjected to an electrostatic force, the molecular interaction such as van der Waals force and Casimir force appears in a significant contribution to the attraction between nanobeam and substrate as the gap between nanobeam and substrate gradually decreases [18,19]. The critical electric potential and the corresponding maximum deflection which lead the nanobeam to collapse onto the substrate, are called the pull-in voltage and pull-in deflection, respectively [20], and are used to evaluate the stability and safety of NEMS. Because of the effect of van der Waals force and Casimir force, the cantilever nano-actuator without external voltage can also collapse onto the substrate [21,22], which is called as the freestanding behavior. The detachment length and minimum gap are two basic design parameters describing the freestanding behavior in NEMS [4,21,23,24]. The detachment length is the maximum length for nano-actuator that would not stick to the substrate under van der Waals force and Casimir force. The minimum gap is the critical initial distance between the lower surface of nano-actuator and the upper surface of substrate. Therefore, the investigation on the freestanding behavior of nano-actuator can enhance the reliability of design for nano-actuator.

Many researches on the electromechanical characteristics of NEMS have been presented so far. Ramezani et al. [19,25,26] proposed a distributed parameter model to analyze a cantilever type of nano-actuators and derived a nonlinear governing equation by using the Green's function. By comparing a lumped parameter model, they found that the lumped parameter model underestimates the pull-in parameters of the nano-actuators. Based on a large deflection model, the pull-in instability of an

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http://dx.doi.org/10.1016/j.sna.2014.10.009

electrostatically micro-cantilever actuator was analyzed by Chaterjee and Pohit [27]. They found that the results would be much improved when higher order terms of nonlinearity are taken into account during static and dynamic analysis. Yang et al. [28] gave a solving method for the pull-in instability of nano-switches with electrostatic force and intermolecular force by utilizing a linear distributed load model.

Generally, the scale effect of nanostructure is compatible with the size of molecular and/or atomic interactions, where the long range forces (nonlocal characteristics) between atoms should be considered. To consider the scale effect on the physical problem of micro and nano-structures, Eringen [29–31] presented the non-local elastic theory containing the long-range force between atoms by introducing the internal length scale into the constitutive equations as a material parameter. Nonlocal elasticity theory has been widely utilized to investigate the various physical problems of micro-/nano-structures, where the effects of nonlocal scale parameter on the physical and mechanical behaviors of micro-/nano-structures are obvious by comparing the results from classical local elasticity theory [32–36]. The MD results show that the nonlocal beam theory can present a better prediction for the dispersion of flexural waves in single-walled carbon nanotubes than other classical beam theories [37].

Surface effect has become more and more important in analyzing the size-dependent characteristics of nano-structures with the higher ratio of surface region to bulk [38,39]. Surface tension or surface force occurs for the atoms locating in near surface layer, because surficial atoms experience different surrounding environment from the atoms in the bulk. Consequently, the physical properties of surface layer are obviously different from that of the bulk of nanoscale material and structure [40,41]. Koochi et al. [42] studied the influence of surface effect including surface force and surface elasticity on the pull-in instability of a cantilever nano-actuator. It is seen that surface effects cause the nano-actuator to change the electromechanical coupling performances. Utilizing finite element method (FEM), Eltaher et al. [43] studied the coupled characteristics of surface properties and nonlocal elasticity on vibration behaviors of nanobeam. It is found that the surface effects increase the fundamental frequency as the thickness decrease.

Carbon nanotubes (CNTs) having higher strength ratio and stiffness ratio as one of promising reinforcement have been widely applied in the field of micro-/nano-composite [44,45]. With rapid development of MEMS and NEMS, there exists urgent demand for micro-/nano sensor and actuator devices having high sensitivity and high mechanical stiffness. CNTs have been widely utilized in micro-/nano-sensor and actuator due to their excellent physical and mechanical properties [36,46,47].

To authors' knowledge, the report of investigation into the pull-in instability characteristics and freestanding behavior of CNTs reinforced electrostatic nano-actuator is few in literatures so far. Therefore, it is significant to study the electromechanical characteristics of CNTs reinforced NEMS considering the nonlocal scale characteristics and surface effect. Some numerical methods to solve the boundary value problem (BVP) for pull-in instability of nano-switch, nano-actutor and nano-tweezers were presented in literatures. Utilizing a differential quadrature method (DQM), Civalek and Demir [32] solved the BVP induced by the governing equation of microtubules subjected to constant loading. Based on finite element method (FEM), Eltaher et al. [43] obtained the numerical result of nonlinear BVP. Mousavi et al. [4] studied the mechanical characteristics of nonlocal nanobeam subjected to nonlinear dispersion force by means of DQM.

This paper reports the result of an investigation into the influence of CNTs reinforcement, scale-dependent behavior and surface force on the electromechanical coupling characteristics of cantilever NEMS. The pull-in instability and free-standing behavior of the CNTs reinforced cantilever NEMS are also investigated subjected to electrostatic force and intermolecular force, respectively. Here, van der Waals force is generally considered when the gap between cantilever nanobeam and substrate is less than 20 nm, and Casimir force as the macro attractive interaction from the fluctuation of quantum field is considered when the gap is larger than 20 nm [38,39]. By solving one extremely nonlinear fourth-order governing equation derived, the influences of CNTs volume ratio, nonlocal elasticity, surface effect, van der Waals interaction and Casimir force on the electromechanical coupling characteristics of CNTs reinforced cantilever NEMS are obtained and discussed.

2. Theory and governing equations

Fig. 1 shows a CNTs reinforced cantilever nano-actuator subjected to the electrostatic force, van der Waals force and Casimir force. The CNTs reinforced nano-actuator is considered as the long and thin cantilever beam with the length L, width w and thickness h. The initial gap between CNTs reinforced cantilever beam and substrate is g. The coordinate system is fixed to the neutral axis at the left end of the cantilever nanobeam, where x and z present the horizontal and vertical direction, respectively.

2.1. Electrostatic loads

CNTs reinforced nano-actuator as shown in Fig. 1 is subjected to electrostatic loads containing fringing field effect by the first order correction assumption. The electrostatic force per unit length exerted on the CNTs reinforced nano-actuator is given by [48]

$$f_{elec} = \frac{\varepsilon_0 w V_e^2}{2(g-u)^2}\left(1 + 0.65\frac{g-u}{w}\right) \tag{1}$$

where $\varepsilon_0 = 8.854 \times 10^{-12}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$ is the permittivity of vacuum, V_e is the applied voltage and $u = u(x)$ is the mid-plane deflection of CNTs reinforced cantilever nano-actuator. The intermolecular interaction between cantilever nano-actuator and substrate induces the van der Waals force per unit length exerted on the CNTs reinforced cantilever nano-actuator, as follows [19]:

$$f_{vdW} = \frac{Aw}{6\pi(g-u)^3} \tag{2}$$

where A is the Hamaker constant.

The Casimir force as the macro effect of quantum field fluctuation per unit length exerted on the CNTs reinforced cantilever nano-actuator is given by [42]

$$f_{Casimir} = \frac{\pi^2 \hbar c w}{240(g-u)^4} \tag{3}$$

where $\hbar = 1.055 \times 10^{-34}$ Js is the Plank's constant divided by 2π and $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$ is the speed of light.

2.2. Effective behaviors of CNTs reinforced-composite

CNTs as reinforcement are taken as uniform distribution in the bulk of cantilever nano-actuator. The property of the CNTs reinforced cantilever nano-actuator is considered as isotropic, and the matrix is made of silicon material. According to the extended rule of mixture [46,49], the effective Young's modulus of CNTs reinforced cantilever nano-actuator are given by

$$E_b^{eff} = \eta V_{cnt} E^{cnt} + V_m E^m \tag{4a}$$

Generally, when the cantilever nanobeam is reinforced by CNTs, the CNTs are bonded with a bulk and no CNTs free surface appears, so that the surface energy of CNTs is consumed. Based on the above viewpoint, the surface Young's modulus of CNTs reinforced beam