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Nonlinear pull-in instability of carbon nanotubes reinforced nano-actuator with thermally corrected Casimir force and surface effect

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ABSTRACT

An analytical model of investigating the pull-in characteristics of CNTs reinforced nano-actuator with temperature-dependency subjected to coupled electrostatic loading, dispersion forces as van der Waals and thermally corrected Casimir force, and surface stress are derived based on von Karman's geometric nonlinearity and surface elasticity. The results illustrate that increment of volume fraction of CNTs enhances the structural stiffness and leads to the increases of pull-in voltage of CNTs reinforced nano-actuator; the growth of temperature increases the axial compression stress and thus decreases the pull-in voltage; and free-standing behavior depends on the characteristic scale of the CNTs reinforced nano-actuator. The doubly-clamped and doubly-supported configuration of nano-actuator are considered and the pull-in voltage of doubly-clamped nano-actuator is larger than that of doubly-supported type. Casimir force with thermal correction significantly depends on the temperature and initial gap between electrodes. The results show the difference between Casimir force with and without thermal correction is small within couples of nanometers gap but the effect of Casimir force on pull-in instability of CNTs reinforced nano-actuator cannot be neglected.

1. Introduction

With the continuous evolution of micro-/nano-electro-mechanical systems, namely, MEMS/NEMS, the trend of equipment miniaturization greatly promotes the advancement of various electrostatically actuated devices, such as micro-mirrors [1,2], micro-motors [3], micro/nano-sensors [4], micro/nano-switches [5,6], nano-tweezers [7] and micro/nano-resonators [8,9]. However, the pull-in instability as an undesirable operational state presents tremendous challenge in designing and fabricating novel electrostatically actuated MEMS/NEMS devices [10]. The pull-in instability is generally considered as a structural instability deriving from the coupling effect of elastic force and electrostatic interaction. So far, the mechanism of pull-in instability involved is still not completely understood, although many researchers have extensively investigated the pull-in analysis in order to avoid pull-in and enhance the reliability of structures from theoretical modeling, numerical simulation, design, fabrication process and operation strategy.

The typical nano-actuators are modeled as one conductive nanobeam suspending over a substrate. When the electrical voltage exerted on the nano-actuator increases, the deflection of nano-actuator gradually enlarges; but when the electrical voltage is larger than a certain value, the nano-actuator happens to collapse onto the substrate. This breakdown process is called pull-in stability, and the correspondent critical voltage and deflection of nano-actuator are called pull-in voltage and pull-in deflection, respectively.

Van der Waals force as the essential interaction among molecules, atoms and induced dipole particles, originates from the dipole field of one atom reflected back by its adjacent atom which has been polarized by this field [11]. For nanoscale devices and structures, van der Waals force become dominant when the initial gap of two electrodes is less than characteristic wave length of material (greater than 20 nm). When the separation of macroscopic bodies is larger than 20 nm, the influence of finite wave propagation of speed of light becomes crucial and the resulting wave retardation must be accounted for the nanoscale structures. The interaction of multiple dipole particles within two macroscopic solids incorporating retarded effect is described as Casmir force [12].

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Furthermore, recent experimental observation elucidates the relationship of Casimir force with thermal effect apart from the quantum fluctuation of the electromagnetic field. A. Sushkov et al. first observed the thermal effect of Casimir force by measuring the force at the distances from 0.7 μm to 7 μm, called thermal Casimir force [13]. The results indicate that the thermal effect of Casimir force are dominant at large distances (greater than 1 μm), whereas rather small at short distance (less than 1 μm). But the present experimental equipment cannot accurately measure the thermal effect of Casmir force at distances down to 100 nm, since the systematic error of equipment might overwhelm the small correction of thermal effect [14]. However, to investigate the thermal effect of Casmir force at less than 100 nm on pull-in instability of nano-devices, the theoretical prediction of thermally-corrected Casmir force can be proposed based on the relevant theory of quantum electrodynamics. It should be noted that to author's acknowledge, there is few study on pull-in instability of nano-devices with consideration of temperature-dependent Casmir force [15].

Carbon nanotubes (CNTs) reinforced composites have attracted enormous interest from researchers since CNTs as promising reinforcement have excellent mechanical and physical behaviors with low density [16]. Furthermore, high charge carrier mobility, conductivity, light weight, low fabrication cost and fine stretch ability enable CNTs to have great potential in application of flexible electronics and electromechanical devices [17]. So far, single-walled carbon nanotubes (SWCNTs) as the channel material are assembled into a matrix thin film in field-effect transistors (FETs) [18]. In addition, CNTs based TEs film has been used to fabricate pressure and strain sensors in application of touch screen panels and displays. With the increasing development of nanofabrication techniques, more and more CNTs based MEMS/NEMS devices will be fabricated and ameliorated for meeting future versatile demanding.

In recent years, considerable accounts of investigation have been devoted into the pull-in behaviors of micro/nano-actuators [10]. Continuum Mechanics as one of sound approaches has the strength to be employed to model and analyze the variety of complicated nanoscale structures. Couples of effective mathematical models, such as spring model [19], distributed parameter model [20], lumped parameter model [21], linear supposition model [22] and linear distributed model [23], are presented in the past decade, and they can basically reflect the characteristics of pull-in instability of MEMS/NEMS. It is well known that the nanoscale materials and structures have significant side-dependent property different from macroscopic world. Therefore, several crucial theories with consideration of nanoscale features, including nonlocal elastic theory [24–28], couple stress theory [29–32], strain gradient elasticity theory [33–35] and surface effects [5,36–39], have been also proposed to better elucidate the pull-in instability of nano-actuators recently. In this paper, the surface effects are utilized to characterize the size effect of nano-actuator. The surface of solid materials is regarded as a layer ignoring thickness that has the own atom arrangement and no boundary confine in outer surface. So surface atoms experience different surrounding environment and appear its own physical property instinct from the bulk [40,41]. The Young-Laplace equation was originally used to define surface and interface tension of fluids, but Gurtin et al. developed one continuum model of surface elasticity where Young–Laplace equation was extended to solids [42–44].Therefore, based on Gurtin's theory, surface elasticity and surface residual stress are described as elastic property of surface layer and distributed force induced by the residual surface tension under bending, respectively [45]. As the size of nano-actuator decreases, the surface effects become significant and thus must be considered to understand pull-in instability of nano-actuators.

The environmental temperatures play an important role in regular work of MEMS/NEMS. In particular, change of temperature as one crucial factor can influence the accuracy and reliability of working performance of electrostatic nano-actuators [7,46,47]. For thermoelastic behaviors, temperature changes give rise to thermal strains or thermal stress of solid materials under different constrained conditions. In previous studies, the coefficient of thermal expansion (CTE) is usually considered as one constant independent of temperature. However, numerous researches show that the CTEs of solids significantly depend on environmental temperature. Thus, the temperature-dependent CTEs of CNTs and matrix materials are employed to investigate pull-in instability of electrostatic CNTs reinforced composite nano-actuators under changing temperature environment [48,49].

This work focus on the nonlinear pull-in instability of CNTs reinforced nano-actuators under the nonlinear electrostatic force, surface effect and dispersion forces, and then GDQ method is utilized to numerically solve the nonlinear governing equation with temperature-dependency. The effect of volume fraction of CNTs, temperature change, dispersion forces as van der Waals interaction and thermally corrected Casimir force, geometrical parameters of nano-actuator and free-standing behavior are comprehensively discussed in this paper. The new results might be useful to understand the electro-thermo-mechanical coupling influences on the pull-in characteristics of CNTs reinforced nano-actuator.

2. Theory and model

Fig.1(a) illustrates the sketch of a CNTs reinforced composite nano-actuator composed of a doubly-clamped nanobeam with the length L, width w and thickness h, where the CNTs nano-actuator is subjected to the coupling influence of the electrostatic force with fringing field effect, dispersion forces (van der Waals force and Casimir force) and thermal loading. The initial gap between CNTs nano-actuator and the substrate is g. Assume that x is the coordinate along the span of CNTs nano-actuator with its origin at the left end, and z is the perpendicular to the surface of CNTs nano-actuator, defined to be positive in the downward direction.

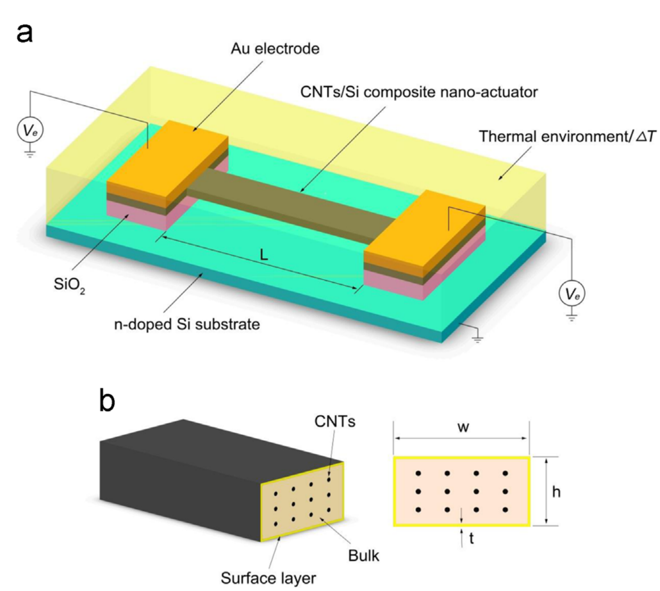

Fig. 1. (a) Sketch of CNTs reinforced electrostatic nano-actuator system under thermo-electric loads. (b) Cross section of CNTs reinforced nano-actuator with surface layer.