Applied Mathematical Modelling 43 (2017) 321–336

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Thermal and surface effects on the pull-in characteristics of circular nanoplate NEMS actuator based on nonlocal elasticity theory

W.D. Yang, W.B. Kang, X. Wang*

School of Naval Architecture, Ocean and Civil Engineering (State Key Laboratory of Ocean Engineering), Shanghai Jiaotong University, Shanghai 200240, P R China

ARTICLE INFO

Article history:
Received 20 October 2015
Revised 9 September 2016
Accepted 10 November 2016
Available online 3 December 2016

Keywords:
Thermal loading
Surface effect
Pull-in voltage
Circular nanoplate
Casimir force
Nonlocal elasticity

ABSTRACT

This paper aims to investigate the coupling influences of thermal loading and surface effects on pull-in instability of electrically actuated circular nanoplate based on Eringen's nonlocal elasticity theory, where the electrostatic force and thermally corrected Casimir force are considered. By utilizing the Kirchhoff plate theory, the nonlinear equilibrium equation of axisymmetric circular nanoplate with variable coefficients and clamped boundary conditions is derived and analytically solved. The results describe the influences of surface effect and thermal loading on pull-in displacements and pull-in voltages of nanoplate under thermal corrected Casimir force. It is seen that the surface effect becomes significant at the pull-in state with the decrease of nanoplate thicknesses, and the residual surface tension exerts a greater influence on the pull-in behavior compared to the surface elastic modulus. In addition, it is found that temperature change plays a great role in the pull-in phenomenon; when the temperature change grows, the circular nanoplate without applied voltage is also led to collapse.

1. Introduction

In recent years, nano-electromechanical systems (NEMS) play more and more roles in nano-technology [1–4], due to the lower energy consumption and better electromechanical characteristics. Many advances in the technology of NEMS have accelerated engineering applications which have been used in nano-switches [5–9], nano-tweezers [10–12], nano-sensors and nano-actuators [13–16].

NEMS are usually modeled to be a conductive deformable body suspending above the substrate [17,18], where the deflections of the deformable body is induced by the electrostatic force generated from a voltage applied between the body and substrate. When the applied voltage reaches a critical value, the elastic restoring force in the deformable body couldn't balance the electrostatic force, so that the NEMS eventually collapses, and the deformable body will be attached to the substrate. This process is known as the pull-in instability which has been experimented [19–21]. In this case, the maximum bending deflection of deformable body is called pull-in displacement, and the critical voltage between the body and substrate is called pull-in voltage [20,22].

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

http://dx.doi.org/10.1016/j.apm.2016.11.023
0307-904X/

In general, NEMS are modeled by the conductive nano-beam and the substrate. However, the NEMS devices in a circular nano-plate possess the more smooth structure than nano-beam because no corner and sharp edges induce higher residual stress [23,24]. Some researches on the pull-in instability of microplate have been presented so far. Nabian et al. [25] proposed a distributed model to investigate the pull-in instability of a circular microplate subjected to non-uniform electrostatic pressure and uniform hydrostatic pressure by using the step by step linearization method and finite difference method. By comparing the two actuation mechanism, the different effects on each actuation mechanism have been studied. Liao et al. [26] gave a fifth-order Taylor series expansion method for the pull-in instability by developing a continuous model, the results show the ratio of the dynamic to static pull-in voltages influenced by squeezed-film effect induced by the air gap. Based on reduced-order model, the pull-in instability of micro-electromechanical rectangular and circular plates was analyzed by Batra et al. [27] They found the Casimir force could influence the pull-in instability.

Generally, with the higher ratio of surface region to bulk, it is necessary to take surface effect into account in analyzing the size-dependent characteristics of nano-structure [28]. Because of the surficial atoms experience different surrounding environment from the atoms in the bulk, residual surface tension or surface modulus appears for the atoms in near surface layer. Therefore, it shows obviously different physical properties from the buck of nano-structure [29].Wang et al. [30] studied the effect of surface elasticity and residual surface stress the critical force of axially buckling of a nanowire. It is seen that both surface elasticity and residual surface tension affect the buckling behavior of nanowires. Utilizing generalized differential quadrature (GDQ) method, Ansari et al. [31] studied the surface stress effect on the vibrational response of circular nanoplates with various Edge Supports. It is found that the influence of surface stress can be different for various circumferential mode numbers, boundary conditions, plate thicknesses, and surface elastic constants. Rokni et al. [20] investigated surface and thermal effects on the pull-in behavior of doubly-clamped grapheme nano-ribbons under electrostatic and Casimir force, it is found that the surface effects become more dominant as the number of GNRs decreases.

Moreover, as the device size gradually decreases into the nanoscale, the dependence of material behaviors on size becomes a crucial factor in designing such devices with predictable and reproducible operation. The size-dependent properties of nanostructures have been observed in experiment. The conventional elasticity theories cannot completely capture the size-dependent characteristics of nanostructures, Eringen's nonlocal elasticity theory, due to considering the long-range forces between solids where the stress at a referenced point depends on the strains at all points in elastic body, has been widely utilized to investigate the size-dependent mechanical behaviors of various nano-structures [32].

In addition, NEMS has been attracting much more attention in engineering applications in different temperature environment, so its value to investigate the influence of thermal loading on the pull-in instability of edge-clamped nanoplate. Rokni et al. [20] studied the thermal loading effect on the pull-in instability of graphemenanoribbons, and it is shown that the nanoribbons become more stable with the increase of temperature change because of the negative thermal expansion coefficient. The recent experimental observation shows the relationship of Casimir force with thermal effect apart from the quantum fluctuation of the electromagnetic field. Sushkov et al. [33] first observed the thermal effect of Casimir force by measuring the force at the distances from 0.7 to 7 µm, called thermal corrected Casimir force. But it is so far difficult to accurately measure the thermal effect of Casmir force at distances down to 100 nm by present experimental equipment, for the systematic error of equipment could overwhelm the small correction of thermal effect. On the other hand, the theoretical prediction of thermally-corrected Casmir force can be proposed to study the pull-in behaviors of NEMS-based devices.

The investigation into the effects of surface behavior and thermal loading on the pull-in instability characteristics of nanoplate is few in literatures so far according to author's knowledge, therefore, it is significant to study the pull-in instability of edge-clamped circular nanoplate under thermal loading. In this paper, the model is composed of circular nanoplate with clamped ends and electric substrate, where Casimir force [34–36] and thermal loading are considered. By using analytical procedure, the deflection of circular nanoplate is described by the mode function of the circular nanoplate by using vibration theory, and the dimensionless pull-in displacements and voltages are obtained. It is seen from the results that the influences of surface behavior, thermal loading and Casimir force on the pull-in instability of edge-clamped circular nanoplate are explored. It is also seen that compared to the pull-in displacements and pull-in voltages of nanoplate, the influence of environment temperature change on the pull-in voltage is larger than that on the pull-in displacement.

2. Nonlocal equilibrium equation and solution procedure

Fig. 1a, b illustrates an electromechanical coupling system composed of a circular nanoplate with clamped edges and a substrate, where there exists initially parallel gap between them. The electromechanical coupling system is subjected to electrostatic force, Casimir force, thermal loading and surface residual stress. The radius and thickness of the circular nanoplate are r_0 and h, respectively, where $5h < 2r_0$. The initial gap between nanoplate and substrate is d. The polar coordinate system ($or\theta z$) is fixed at the center of the middle surface of circular nanoplate, where r, θ and z present the radial, angle and vertical direction.

When a voltage V_e is applied between nanoplate and substrate, the electric potential difference appears between them, and the charges are distributed on the circular nanoplate and the substrate, so that it will generate the electrostatic force, where the force per unit area exerted on the circular nanoplate is written as [25]

$$q_e = \frac{\varepsilon_0 {V_e}^2}{2[d - w(r)]^2}, \tag{1}$$