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On the dynamic instability of nanowire-fabricated electromechanical actuators in the Casimir regime: Coupled effects of surface energy and size dependency

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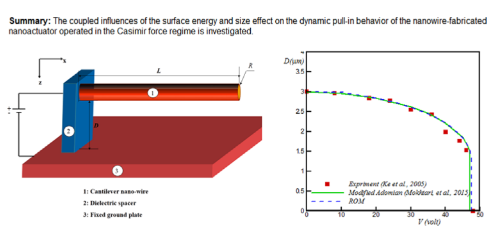
HIGHLIGHTS

- Static and dynamic pull-in instability of a nanowire-fabricated actuator is studied.
- Casimir force is modeled using Drichlet mode assumption.
- The coupled effects of surface energy and size phenomenon are incorporated.
- The higher order surface stress components are incorporated in model.
- The influence of structural damping is considered.

GRAPHICAL ABSTRACT

Summary: The coupled influences of the surface energy and size effect on the dynamic pull-in behavior of the nanowire-fabricated nanoactuator operated in the Casimir force regime is investigated.



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ABSTRACT

Herein, the dynamic pull-in instability of cantilever nanoactuator fabricated from conductive cylindrical nanowire with circular cross-section is studied under the presence of Casimir force. The Gurtin–Murdoch surface elasticity in combination with the couple stress theory is employed to incorporate the coupled effects of surface energy and size phenomenon. Using Green–Lagrange strain, the higher order surface stress components are incorporated in the governing equation. The Dirichlet mode is considered and an asymptotic solution, based on the path integral approach, is applied to consider the effect of the Casimir attraction. Furthermore, the influence of structural damping is considered in the model. The nonlinear governing equation is solved using analytical reduced order method (ROM). The effects of various parameters on the dynamic pull-in parameters, phase planes and stability threshold of the actuator are demonstrated.

1. Introduction

Nanowires have attracted many attentions in developing advanced nano-electromechanical systems (NEMS). Nanowire-fabricated actuators are potential for a wide range of applications including bio-engineering, medicine, nanoelectronics, sensing, etc. [1–4]. A typical nano-actuator is constructed from a moveable nanowire suspended over a fixed conductive plane via a dielectric spacer in between. By applying DC voltage difference between the components, the nanowire deflects toward the ground electrode until at a critical (pull-in) voltage, it adheres the ground. This

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critical voltage limits the range of stable actuation (actuating range) of the actuator. Therefore, predicting the stable actuating range and the pull-in instability threshold are important issues for designing reliable nano-actuators [5–10]. It has been well established that at the nano-scale separations (typically several ten nanometers) the presence of vacuum fluctuations, i.e. Casimir force, substantially affects the pull-in instability of NEMS. Many researchers have been investigated the effect of Casimir force on adhesion and pull-in characteristics of ultra-small systems [11–16]. The geometry of the interacting surfaces plays an important role on the strength of the Casimir attraction between bodies [17–20]. Almost all previous researches in this area have dedicated to the pull-in behavior of the nano-actuators with planar configurations. Recently, few researchers have incorporated the effect of Casimir force in the static pull-in of actuators fabricated from nanowires with cylindrical geometries [21,22]. However, no work has been dedicated to modeling the dynamic instability of such nanowire fabricated structures in the Casimir regime. One of the reliable approaches for modeling the Casimir force between non-planar interacting objects is the path-integral approach. This approach can be employed as a precise theory for approximating the Casimir attraction between real non-planar structures such as spheres, sphere-plane and cylinder-plate geometries [23,24]. In this work, an asymptotic solution, based on the path integral approach, is applied for modeling the Casimir regime.

Nano-scale structural elements exhibit large surface area to volume ratio. Therefore, the crucial influences of surface layer on the behavior of the nanostructures might be considerable [25,26]. A continuum theory has been developed by Gurtin and Murdoch [27] to model the influence of surface layerin miniature structures. This theory has been widely applied to investigate the surface effects on elastic behavior of beam-type nano-structures [28–30]. Recently, some researchers have investigated the instability of NEMS structures considering the impact of surface energy [30–35]. Fu and Zhang [30] have applied a modified continuum model to investigate the pull-in behavior of electrically actuated double-clamped nano-bridges incorporating the surface effects. Shaat and Mohamed [35] developed a size-dependent electrostatic model for micro-actuated beams by considering the microstructure and surface energy effects.

Beside the surface energy, the effect of microstructure i.e. size dependency of material characteristics at small scale is another crucial issue that might be necessary to be considered in modeling NEMS. Experiments show a hardening behavior in the elastic resistance of the materials such as conductive metals and nanowires as the dimensions become comparable to the internal material length scale [36,37]. The classical continuum theory is not able to model the effect of microstructure and size-dependent behavior of materials and structures at small scales. In this regards, the non-classical theories such as non-local elasticity [38], couple stress theory (CST) [39], strain gradient theory [36], modified couple stress theory [40], etc. have been developed to consider the size effect in theoretical continuum models. The CST theory can be considered as the special case of the micropolar theory by considering the rotation vector of the microstructure identical with those of macrostructure. This assumption reduces the number of material length scale parameters from four in the micropolar theory to two in the couple stress theory [41]. While other size dependent theories have been applied by many researchers to investigate miniature structures, less works have been conducted on modeling the ultra-small structures using the CST. Anthoine [42] studied pure bending of a circular cylinder by using the CST. The free transverse vibrations of Euler beam based on the CST was studied in Ref. [43]. Fathalilou et al. employed the CST to investigate the size dependent bifurcation behavior of an electro statically-actuated nano-beam [44].

In the present study, the authors demonstrate the coupled influences of the size effect and surface energy on the static and dynamic pull-in instability of NEMS actuator fabricated from cylindrical nanowire and operated in Casimir regime. The CST in conjunction with Gurtin–Murdoch surface elasticity are applied to obtain the constitutive governing equations of the cantilever nano-actuator. Using Green–Lagrange strain, the higher order surface stress components are incorporated in the governing equation. Based on the path integral approach, an asymptotic solution of the Dirichlet mode is considered for modeling the Casimir attraction. Analytical reduced order method (ROM) is employed to solve the nonlinear governing equation of the system.

2. Theoretical model

A typical cantilever NEMS actuator fabricated form nanowire is shown in Fig. 1. The length and the radius of the nanowires are L and R, respectively. The initial gap between the ground and nanowire is D.

2.1. Size effect

In the CST, the strain energy is assumed to depend on the rotation gradient, in addition to the strain. The rotation tensor (ω) can be explained as:

$$\omega_{ij} = \frac{1}{2}\left(u_{i,j} - u_{j,i}\right) = -\omega_{ji} \tag{1}$$

The rotation vector (θ) is defined as:

$$\theta_i = \frac{1}{2}e_{ijk}u_{k,j} \tag{2}$$

where e_{ijk} is the permutation symbol. Eliminating the displacement u in (1) and (2), the following relations are obtained:

$$\omega_{ij} = e_{ijk}\theta_k \tag{3-a}$$

$$\theta_i = \frac{1}{2}e_{ijk}\omega_{jk} \tag{3-b}$$

The gradient of rotation (κ) is defined as:

$$\kappa_{ij} = \theta_{j,i} = \frac{1}{2}e_{jkl}\omega_{kl,i} \tag{4}$$

Substituting Eq. (3) in (4) one can obtain:

$$\kappa_{ij} = \frac{1}{2}e_{jkl}u_{l,ki} \tag{5}$$

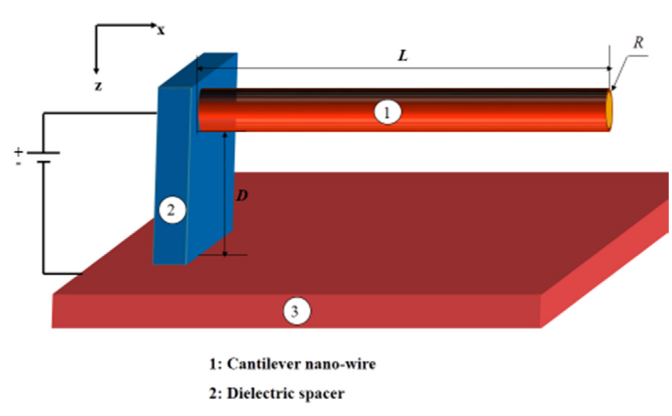

Fig. 1. Schematic representation of typical nanowire based actuator.