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Theoretical modeling of the Casimir force-induced instability in freestanding nanowires with circular cross-section

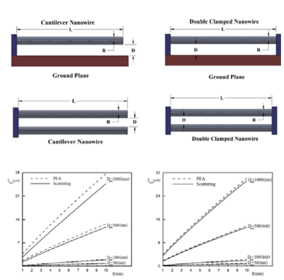
Amin Farrokhabadi [a], Naeime Abadian [b], Randolph Rach [c], Mohamadreza Abadyan [d,*]

[a] Department of Aerospace Engineering, Semnan University, Semnan, Iran
[b] Physics Department, Qom Branch, Islamic Azad University, Qom, Iran
[c] 16 South Maple Street, Hartford, MI 49057-1225, USA
[d] Islamic Azad University, Shahrekord Branch, Shahrekord, Iran

HIGHLIGHTS

- Effects of the Casimir force on the instability of freestanding Cylinder–Plate and Cylinder–Cylinder geometries are investigated.
- The proximity force approximation (PFA) for small separations and Dirichlet asymptotic approximation for large separations are considered.
- The detachment length and minimum gap, both of which prevent the Casimir force-induced adhesion, are computed.

GRAPHICAL ABSTRACT



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ABSTRACT

The Casimir force can induce instability and adhesion in freestanding nanostructures. Previous research efforts in this area have exclusively focused on modeling the instability in structures with planar or rectangular cross-section, while, to the best knowledge of the authors, no attention has been paid to investigate this phenomenon for nanowires with circular cross-section. In this study, effects of the Casimir force on the instability and adhesion of freestanding Cylinder–Plate and Cylinder–Cylinder geometries are investigated, which are commonly encountered in real nanodevices. To compute the Casimir force, two approaches, i.e. the proximity force approximation (PFA) for small separations and Dirichlet asymptotic approximation (scattering theory) for large separations, are considered. A continuum mechanics theory is employed, in conjunction with the Euler-beam model, to obtain constitutive equations of the systems. The governing nonlinear constitutive equations of the nanostructures are solved using two different approaches, i.e. the analytical modified Adomian decomposition (MAD) and the numerical finite difference method (FDM). The detachment length and minimum gap, both of which prevent the Casimir force-induced adhesion, are computed for both configurations.

1. Introduction

With recent advances in nanotechnology and miniaturization, nanotubes and nanowires have become one of the most common constructive elements in fabricating nanoelectromechanical systems (NEMS). Generally, the behavior of such nanosystems is influenced by small-scale quantum electrodynamical interactions such as the Casimir force and van der Waals attraction. Among the small-scale interactions, vacuum fluctuation forces, i.e. the Casimir force becomes comparable to, or even dominant over, other small-scale attractions in sub-micron separations [1]. In recent decades, the Casimir effect has attracted increasing experimental [2–3] and theoretical interest [4–9]. Lamoreaux [10] used a torsion

* Corresponding author.
E-mail addresses: amin.farrokh@profs.semnan.ac.ir (A. Farrokhabadi), abadiannaeime@yahoo.com (N. Abadian), tapstrike@gmail.com (R. Rach), abadyan@yahoo.com (M. Abadyan).

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pendulum with an electromechanical feedback system to measure the Casimir force between a spherical surface and a flat plate. Mohideen et al. [11] measured the Casimir force between a sphere mounted on the tip of a flexible cantilever and a flat plate by an atomic force microscope. Chan et al. [12] measured the Casimir force between a sphere and a flat plate in a microelectromechanical system (MEMS) using a micromachined torsional device. Recently, researchers have demonstrated the Casimir effect between two micromachined silicon components by integrating a force-sensing micromechanical beam and an electrostatic actuator on a single chip [13].

In order to achieve highly precise results, a careful analysis of the Casimir force corrections due to the geometry of interacting bodies, finite conductivity of the metal surfaces, roughness, non-zero temperature, etc. is essential [14–19]. It has been well established that the geometry of the interacting surfaces plays an important role on the strength of the Casimir attraction between bodies. The Casimir interaction has been investigated for several geometries including parallel plates [20], a rectilinear piston [21], plate–sphere interaction [22], parallel cylinders [23], plate–cylinder [24], etc. A simple but uncontrolled method for approximating the Casimir interaction between non-planar geometries is the proximity force approximation (PFA). According to the PFA, a nanosystem is treated as a sum of infinitesimal parallel plates [14]. However, this approach is not able to provide reliable general expressions even for simple geometries. Unfortunately, the total interaction of a system of particles cannot be obtained by simply adding the forces between all pairs. Instead, one must also consider higher-order interactions that become increasingly important in nanoseparations. While shape and geometry can strongly influence two-body Casimir interactions, it is also important to understand the consequences of the non-additivity of fluctuation forces. There are other approaches, which include the semi-classical method [25], optical approach [26], the multi-scattering method [27], the Monte Carlo method [28], that can be used to more precisely approximate the vacuum fluctuation force. The multi-scattering approach [29–31] was successfully applied by previous researchers as a powerful approach to approximate the Casimir force between different structures, e.g., spheres, sphere-plane and cylinder-plane.

As the dimensions of electronic and mechanical systems are reduced to the nanometer scale, the vacuum fluctuations can strongly interfere with the electromechanical response of nanosystems [30,32,33]. On the other hand, movable elements of nanodevices may become unstable and stick together officiously due to the strong attractive Casimir force, impeding their operation [34,35]. The Casimir force can also induce undesired adhesion in freestanding nanostructures during the fabrication and manufacturing stages. Therefore, this force should be taken into account in the design, manufacture and operation of nanoscale devices [34,35]. It is interesting for scientists to evaluate the magnitude of the Casimir force and consider its effects on the instability of nanosystems, especially electromechanical systems [36–41]. The effect of the Casimir force on the mechanical instability of plates and membranes has been simulated by Batra et al. [42–44] using the finite element method. Moghimi et al. [45] have applied the finite element method to simulate the influence of the Casimir attraction on the dynamic pull-in behavior of nanobeams. A one degree of freedom lumped parameter model has been proposed by Lin and Zhao [46–47] to survey stiction of nanoactuators in the presence of electrostatic and Casimir attractions. Ramezani et al. [48] have used the Green's function to investigate the pull-in parameters of cantilever beam-type actuators under Casimir forces. It should be noted that all the mentioned works have focused on modeling the instability in structures with planar or rectangular cross-section. However, to the best knowledge of the authors, no attention has been paid to investigate this phenomenon in nanosystems with circular cross-section such as nanowires and nanotubes. While the effect of the non-retarded dispersion force, i.e. the van der Waals attraction, on the mechanical instability of beam-type nanostructures with circular cross-section has been investigated previously [49–54], no work has been dedicated to modeling the Casimir force-induced instability in these cylindrical structures. In this regard, modeling of the Casimir force-induced instability is crucial for investigation of the stability performance of nanoactuators, NEMS switches, nanoresonators and nanotweezers that are made of carbon nanorods, metallic nanowires, etc.

Therefore, in the present study, the authors demonstrate the effect of the Casimir force on the mechanical instability of two separate freestanding nanostructures with circular cross-sections including the Cylinder–Plate and Cylinder–Cylinder geometries. Herein, continuum mechanics in conjunction with the Euler beam model are applied to obtain the constitutive governing equations of the nanosystems under the presence of the Casimir force. To solve these nonlinear governing equations, two different approaches, i.e. analytical method and a numerical solution are employed.

2. Theoretical model

Fig. 1 shows the schematic representation of four freestanding nanostructures fabricated from nanowire. Fig. 1(a) and (b) shows the typical cantilever and double-clamped freestanding nanowires suspended over a ground plate, respectively. The movable conductive nanowire can deflect towards the fixed conductive plane substrate due to the presence of the Casimir attraction. This configuration is commonly observed in realistic devices such as NEMS, actuators, probes, resonators, etc. [47]. Fig. 1(c) and (d) presents typical cantilever and double-clamped freestanding parallel conductive nanowires, respectively. The Casimir force can cause the nanowires to deflect toward each other. These configurations can include nanotweezers, other nanodevices, etc. [55].

In the aforementioned structures, the initial gap between the two nanowires or between the ground and nanowire, the length and the radius of the nanowires (with circular cross section) are D, L and R, respectively. In the case of cantilever structures, the boundary conditions are defined as no displacement and rotation as well as traction free at the free end, i.e. no shear force and moment. In the case of double-clamped structures, no displacement and rotation are imposed on both nanowire ends.

2.1. The Casimir energy

The Casimir energy per unit area for conducting parallel infinite flat plates (E_{pp}) separated by a distance D is [14]

$$E_{pp}(D) = -\frac{\pi^2 \overline{h} c}{720 D^3}, \tag{1}$$

where $\overline{h} = 1.05457 \times 10^{-34}$ J s is the reduced Planck's constant and $c = 2.998 \times 10^8$ m/s is the speed of light. This formula can be derived by consideration of the electromagnetic mode structure between the two plates, as compared with free space, and by assigning a zero-point energy to each electromagnetic mode (photon) [14,60]. Relation (1) is the fundamental starting point for the proximity force approximation (PFA). According to the PFA, any complex interacting surfaces can be treated as a sum of infinitesimal parallel plates [14]. For very short separations, the PFA gives the correct zeroth order approximation to the Casimir