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Surface effect on dynamic characteristics of the electrostatically nano-beam actuator[☆]

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ABSTRACT

A nonlinear pull-in behavior analysis of a cantilever nano-actuator was carried out and an Euler–Bernoulli beam model was used in the examination of the fringing field and the surface and Casimir force effects in this study. In general, the analysis of an electrostatic device is difficult and usually complicated by nonlinear electrostatic forces and the Casimir force at the nanoscale. The nonlinear governing equation of a cantilever nano-beam can be solved using a hybrid computational scheme comprising differential transformation and finite difference to overcome the nonlinear electrostatic coupling phenomenon. The feasibility of the method presented here, as applied to the nonlinear electrostatic behavior of a cantilever nano-actuator, was analyzed. The numerical results for the pull-in voltage were found to be in good agreement with previously published results. The analysis showed that the surface effects had significant influence on the dynamic characteristics of the cantilever nano-actuator.

1. Introduction

In recent years, nano-electromechanical system (NEMS) devices have been widely applied in a diverse range of applications, including nano-switches [1], ultrasensitive sensor [2] and RF communication modules [3] and others, and this certainly makes NEMS research a worthwhile field. When a driving voltage is applied between a moveable and a fixed structure, charges are induced on each which causes an electrostatic force to act on both structures. As the movable structure approaches the fixed structure, an elastic force tends to make it return to its previous undeformed position. At a critical voltage, which is known as the pull-in voltage, instability occurs and the cantilever nano-beam collapses onto the fixed structure. This is of critical importance in the design of NEMS-based devices.

New physics has emerged in the consideration of NEMS. For example, the effect of intermolecular forces, such as the Casimir and van der Waals forces [4], may play an important role at the nano-scale. For separations below 20 nm the force between two surfaces (van der Waals attraction), varies as the inverse cube of the separation. When the separation is greater than 20 nm, the force between two surfaces can be described as the quantum Casimir effect, which is proportional to the inverse fourth power of the separation [5]. Ke et al. [6] calculated the effect of van der Waals force on the pull-in voltage of carbon-nanotubes based NEMS switches. Rotkin [7] considered the effect of the van der Waals force on the pull-in gap and obtained analytical expressions for both the pull-in gap and voltage of a general model. Soroush et al. [4] investigated the effect of dispersion forces on the

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pull-in instability of cantilever nano-actuators using the Adomian decomposition method (ADM). ADM is a practical technique for solving initial value problems (IVP), boundary value problems (BVP), linear, nonlinear and even chaotic systems [8–11].

However, in practice, surface effects such as the residual surface stress and surface elasticity must be taken into account when evaluating the pull-in behavior of NEMs actuators since the large surface area to volume ratio of such structures induces a size-dependent change in many actuator material properties. Ma et al. [12] studied the effects of surface energies and the Casimir force on the instability parameters of cantilever NEMS actuators using the Homotopy perturbation method (HPM). Wang and Feng [13] addressed the effects of both surface elasticity and surface residual stress on the buckling and vibrational behaviur of nanobeams. Fu and Zhang [14] used a modified continuum model to investigate the pull-in behavior of an electrically actuated double-clamped nano-beam incorporating surface effects. In these investigations, the influence of the Casimir attraction as well as fringing field effects was neglected. There is an important pull-in parameter which is the detachment length in the design of NEMS actuators. In the absence of a driving voltage, the Casimir force could overcome elastic restoration and lead to collapse of the cantilever nano-beam. For any fixed initial gap between electrodes, the maximum allowable length of the cantilever nano-beam that will not adhere to the fixed electrode is called the detachment length [12].

Differential transformation theory was first introduced by Pukhov [15,16] to solve linear and nonlinear initial value problems in physical processes. Zhao used the same theory as a means of solving the circuit analysis domain. However, in recent years, the differential transformation method (DTM) has been extended to include a wide range of engineering problems. For example, Chen et al. [17] and Liu et al. [18,19] used DTM to investigate the problem of entropy generation within a mixed convection flow with viscous dissipation effects in a parallel-plate vertical channel. The solution of the fractional telegraph equation has been discussed by Biazar and Eslami [20] who also used DTM. DTM also has been successfully employed to solve many types of linear and nonlinear problems in mathematics [21,22] and engineering, including thermal conduction [23] and optimal control systems [24]. DTM is a powerful semi-analytical tool for general engineering and mechanics problems and yields an analytical solution in the form of a polynomial [22].

In this study, cantilever nano-actuators incorporating two issue effects are investigated in a simulation of dynamic behavior. The first issue considered is that of intermolecular activity such as the Casimir force at the nano-scale. The second is the surface effect. Hence, a governing equation based on the Euler–Bernoulli beam model incorporating nonlinear electrostatic and intermolecular forces has been used in the present study. The rest of this paper has been arranged as follows: Section 2 describes the use of a hybrid computational scheme to complete the nonlinear governing equation of the cantilever nano-beam and specify initial and boundary conditions. Section 3 validates the proposed method by comparison of the numerical results obtained for tip displacement and pull-in voltage of a cantilever nano-beam with the analytical results presented in the literature. Also, the hybrid computational scheme is used to analyze the dynamic response of the cantilever nano-beam as a function of the applied voltage. Finally, Section 4 presents some brief concluding remarks. Compared to existing methods such as the finite difference method, the hybrid numerical scheme has the advantages of an explicit physical meaning and is also simpler and much faster.

2. The cantilever nano-actuator modeling

2.1. Model description

Fig. 1 shows the NEMS cantilever-type actuator considered in the present study. As shown, the cantilever nano-actuator is composed of the cantilever beam of length L with a uniform rectangular cross section of thickness h and width w. The initial gap between the movable beam and the fixed electrodes is denoted by g. In practice, existing NEMS fabrication techniques make separations below 20 nm rather problematical. So, in this study, only the Casimir force is considered. The nonlinear governing equation for the distributed parameter model, based on the Euler–Bernoulli beam assumptions, may be written as [12]

$$(EI)_{eff}\frac{\partial^4 z}{\partial x^4} + \rho A\frac{\partial^2 z}{\partial t^2} = F_{elec} + F_{sur} + F_{cas}, \tag{1}$$

where z represents the deflection of the beam, x denotes the position along the beam axis measured from the clamped end, $(EI)_{eff}$ is the effective bending rigidity of the incorporated surface elasticity effect, ρ is the material density, I in Eq. (1) is the moment of inertia of the cantilever nano-beam and is given by $I = wh^3/12$ and $A = wh$ is the cross-sectional area of the beam. F_{elec} and

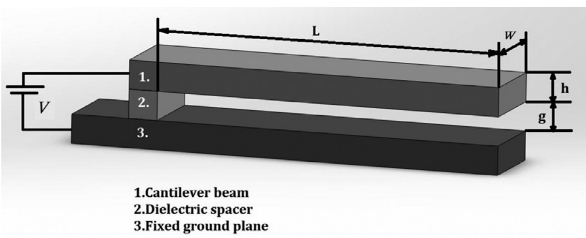

Fig. 1. The cantilever nano-beam system.