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Static characterization and pull-in voltage of a micro-switch under both electrostatic and piezoelectric excitations

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ABSTRACT

In this paper, a comprehensive model of a micro-switch with both electrostatic and piezoelectric actuators, which accounts for the nonlinearities due to inertia, curvature, electrostatic forces and piezoelectric actuator, is presented to demonstrate the mechanical characteristics of such a micro-system. Dynamic equations of this model have been derived by the Lagrange method and solved by the Galerkin method using five modes. The micro-switch beam has been assumed as an elastic Euler-Bernoulli beam with clamped-free end conditions. The electrostatic actuation results are compared with other existing experimental and numerical results. Whereas the major drawback of electrostatically actuated micro-switches is the high driving voltage, using the piezoelectric actuator in these systems can provide less driving voltage and control the pull-in voltage. The study demonstrates that although the effect of nonlinearity due to electrostatic forces on the deflection is larger than other ones, yet a linear behavior can be observed through the balance between nonlinear terms. There are three ways to influence the design and control of the mechanical characteristics of this micro-switch: the softening effect due to electrostatic actuation, the hardening effect due to piezoelectric actuation, and varying the length and thickness of the piezoelectric actuator.

1. Introduction

Micro and Nano electromechanical systems (MEMS and NEMS) have attracted a lot of attention in many applications such as sensors and actuators, and also in energy conversion mechanisms in different engineering applications such as micro-switches. A typical electrostatic micro-switch consists of a conductive movable micro-beam and a fixed actuation electrode placed on a substrate below the micro-beam. When a DC voltage is applied between the micro-beam and electrode, the induced electrical field exerts an electrostatic force on the movable micro-beam, deflecting it towards the fixed electrode; this deflection is called static deflection. At a high-enough voltage, the movable micro-beam becomes unstable and is pulled into the fixed electrode; this puts the micro-switch in the ON position. This phenomenon, which is the result of electrostatic force nonlinearity, is known as the 'pull-in'. The pull-in voltage is of utmost importance in the design of MEMS devices. The design, simulation and modeling of MEMS and NEMS devices are getting increased attention as more equipment is fabricated in micro/nano scales. Therefore, a new idea on the design and modeling of such devices will help in optimizing the efficiency and developing novel concepts in response to ever-increasing demands for new products (Younis, 2011; Zamanian et al., 2010; Xiao et al., 2011). Regarding the design and modeling of MEMS devices, many papers have been published on the development of governing equations and on the dynamic/static analysis of movable beams in micro devices in order to determine specifications such as deflection, natural frequency and pull-in voltage in these systems.

Lizhoung and Xiaoli (2007) studied the static/dynamic behavior of a micro-beam subjected to electrostatic forces. They assumed nonlinear terms due to electrostatic forces and solved these nonlinear equations by using the perturbation method. Shankar et al. (2011) studied a micro-switch to investigate the effect of residual stress gradient on its electromechanical characteristics such as deflection, resonant frequency and pull-in

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voltage. They found that the residual stress gradient is a very important parameter for the prediction of the characteristics of a micro-beam switch.

Xiao et al. (2011) employed the DQM method to obtain the instability characterization of a micro-switch under electrostatic and Casimir forces with four different boundary conditions. They considered geometric (mid-plane stretching) nonlinearity in the governing equation of motion, and their model included homogeneous and non-homogeneous functionally graded materials (FGMs). Wang and Lin (2010) studied the effect of initial gap, fringing fields, residual stress on the pull-in voltage of electrostatically actuated beams. They used numerically shooting method to solve the governing equations. Their results show that the shooting method is a practical approach for the analysis of nonlinear MEMS.

Pasquale and Soma (2010) researched the dynamic behavior of MEMS in electro-mechanical coupling. They compared the obtained experimental and analytical Results and described the dynamic behavior of MEMS in the context of some common experimental problems. Chaterjee and Pohit (2009) analyzed a micro-cantilever under electrostatic actuation with large gap between electrodes. Due to clamped-free boundary condition they assumed shortening effect to derive the equation of motions. In their analysis, nonlinearities due to geometry, inertia and electrical forces were considered. They found the deflections and frequencies of the micro-beam through static and dynamic analysis, respectively. The micro-system models in these researches have only included electrostatic actuation.

The major drawbacks of electrostatically actuated micro-systems are high driving voltage and low reliability; so the use of piezoelectric materials in micro-systems can be appropriate, because these types of materials enjoy advantage such as light weight, rapid response, high operating bandwidth and low power consumption. In addition, the characteristics of piezoelectric materials make them suitable for use as both sensors and actuators in micro/nano scale structures.

Cattan et al. (1999) experimentally investigated the piezoelectric properties of PZT film for use in micro-beams. Li et al. (2002) researched the nonlinear vibration of a composite clamped—clamped micro-beam with curved cross section. They studied the harmonic piezoelectric actuation of this micro-beam experimentally. Xiang and Shi (2009) investigated the static analysis of a functionally graded piezoelectric material under electro-thermal load. They solved static equation by using Airy stress method. They showed the influence of thickness ratio, temperature, functionally graded index and electromechanical coupling on the bending behavior of the system. In 2009, Mahmoodi and Jalili evaluated the nonlinear vibrations of a piezoelectrically actuated micro-cantilever experimentally and analytically. They assumed the effect of applied voltage to the piezoelectric layer as bending moment. They showed that a quadratic nonlinearity term appears in the governing equations due to the presence of piezoelectric actuator (Mahmoodi and Jalili, 2009). Grover and Sharma (2012) obtained analytically the energy dissipation of a piezothermoelastic micro-cantilever subjected to transverse vibrations. Peng et al. (2012) modeled a multi-layer cantilever, which included the layers of buffer, piezoelectric and electrodes installed on the cantilever. In their study, they disregarded the effect of axial force, and compared the results of their proposed model with the experimental and FE simulation results. They also evaluated the effects of bending rigidity and damping on the effectiveness of the proposed system. They declared that their findings are suitable for optimal design and performance improvement of cantilevers under piezo excitation. In these studies, the micro-systems were excited by piezoelectric actuators only.

Despite the fact that piezoelectric materials have some advantages, depositing them on micro-substrates is a time consuming process and may be expensive. In addition, when a micro-system is actuated only through piezoelectric actuators, some of the benefits of electrostatic actuation such as the softening effect (due to electrostatic forces) are lost. Considering the aforementioned advantages and disadvantages of the electrostatic and the piezoelectric actuation methods, researchers and designers have been motivated by the design challenges of MEMS and attempted to apply new ideas and solutions in their designs. Electrostatic as well as piezoelectric excitation in micro-systems can be implemented in order to achieve greater efficiency or pull-in voltage control in these systems (Choil et al., 2012). In 2013 Chen et al. investigated the nonlinear behavior of a piezoelectric laminated micro-cantilever under electrostatic actuation. In their study, they assumed the whole upper and lower surfaces of the micro-cantilever to be covered with piezoelectric actuators as well as their model includes two electrostatic plats that are located upper and lower of the micro-cantilever. They assumed the effect of applied control voltage to the piezoelectric layers as axial force. Their results showed that with increasing the piezoelectric voltage the motion state of the micro-system approaches periodicity also they result suitable for design and control of micro-structures (Chen et al., 2013).

In this work a comprehensive model of a micro-switch with both electrostatic and piezoelectric actuations is presented and formulated for the purpose of determining the maximum deflection and pull-in voltage of this micro-system. The piezoelectric actuator is bonded onto a portion of the micro-switch's surface. The movable micro-switch beam has been assumed as an elastic Euler-Bernoulli beam with clamped-free end conditions; so the shortening effect in this model should be considered, which means that the bending neutral axis does not stretch when the micro-switch beam is deflected. The objectives of this model are; reducing the driving voltage and control the pull-in voltage in micro-switches as well as design a micro device which acts as an actuator-sensor. In this work all nonlinear terms due to inertia, curvature (geometry), electrostatic forces and piezoelectric actuator are considered for a micro-switch with piezoelectric and electrostatic excitations since they play important roles in the micro-scale response. In this research, the effect of each nonlinear terms on deflection of micro system is discussed as well. Also the design parameters of this micro-system are discussed.

2. Problem statement and formulation

A flexible slender micro-beam with uniform rectangular cross section and Euler-Bernoulli beam theory assumption is considered as a movable micro-switch. A clamped-free boundary condition exists and therefore, the micro-beam is called micro-cantilever beam. This micro-cantilever beam can be excited electrostatically by applying a DC voltage (V_e) through an electrode held at distance d. We can disregard the effect of fringing field by assuming that the electrical field everywhere is perpendicular to the micro-switch beam and the fixed electrode. Now we cover the upper surface of this micro-switch with a piezoelectric actuator with the same width as that of the micro-switch and the length of l_p (as shown in the Fig. 1(a)). A DC voltage, P, is applied to the piezoelectric actuator. So two applied voltages exist: one between the micro-switch beam and fixed electrode (V_e), and the other which is applied to the piezoelectric actuator (P).