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Thermal effect on the pull-in instability of functionally graded micro-beams subjected to electrical actuation

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ABSTRACT

The thermal effect on the pull-in instability of functionally graded micro-beams under the combined electrostatic force, temperature change and Casimir force is studied based on Euler–Bernoulli beam theory and von Kármán geometric nonlinearity. Take into consideration the temperature-dependency of the effective material properties, the Voigt model and exponential distribution model is used to simulate the material properties of the functionally graded materials (FGMs). Principle of virtual work is used to derive the nonlinear governing differential equation which is then solved using the differential quadrature method (DQM). A parametric study is conducted to show the significant effects of material composition, temperature change, geometric nonlinearity and Casimir force.

1. Introduction

Micro-Electro-Mechanical Systems (MEMS) can be defined as systems of small dimensions fulfilling a smart function. The devices are typically designed to operate in one or more energy domains due to their unique advantages such as small size, lower power consumption, lower operation cost, increased reliability and higher precision. With MEMS are used more and more widely, numerous analytical, numerical and experimental studies have been conducted on the pull-in instability of the MEMS devices [1–5].

Most recently, the use of functionally graded materials (FGMs) in MEMS structures has been proposed by Craciunescu and Wuttig [6] and Fu et al. [7], since FGMs offer many advantages including improved stress distribution, enhanced thermal resistance, higher fracture toughness, and reduced stress intensity factors that make them very attractive in many engineering applications [8]. Specially, Witvrouw and his co-workers [9,10] developed a multilayer poly-SiGe deposition process for fabricating MEMS structural layers that fulfill all material and economical requirements.

Along with the development of technology, MEMS are expected to be used in high temperature environments. Therefore, the properties of functionally graded MEMS devices under the combined electrostatic force and temperature change are badly in need of investigation. Carbonari et al. found that the material gradient played an important role in improving actuator performance, which could also lead to optimal displacements and coupling ratios with reduced amount of piezoelectric material [11]. Hasanyan et al. discussed the pull-in instabilities of functionally graded MEMS due to the heat generated by an electric current; it was found that the pull-in voltage can be regulated by varying volume fractions of two constituents through the thickness of a functionally graded plate [12]. Jia et al. studied the pull-in instability and free vibration of electrostatically actuated FGM micro-beams allowing for the geometric nonlinearity and intermolecular Casimir force, but without considering the temperature change [13–16]. Mohammadi-Alasti et al. investigated the mechanical behavior of a cantilever FGM micro-beam subjected to a nonlinear electrostatic pressure and a temperature change. Their study showed that a temperature change resulted in the deflection of FGM micro-beam due to the variable thermal expansion coefficient along the thickness [17]. The mechanical behavior of FGM micro-tweezer under DC voltage and temperature variations is investigated by Rezaee et al. [18]; it is found that increase the ceramic percentage increases the system equivalent stiffness. However, two important factors, i.e. geometric nonlinearity and intermolecular force were neglected in their analysis.

The differential quadrature method (DQM) for the solution of linear and nonlinear differential equations was first introduced

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by Bellman et al. [19]. Jang extended DQM to the nonlinear analysis of structural components, where the δ-technique was proposed to eliminate the difficulties in implementing two conditions at a single boundary point [20]. Wang et al. [21] gave a new approach to apply the DQM to the deflection, buckling, and free vibration analysis of beams and plates with various boundary conditions. A generalized and more complete methodology for treating boundary conditions in the DQM is presented by Chen et al. [22]. Moreover, there are new ways of implementing the boundary conditions without using δ-technique. The most known is the GDQ Rule (GDQR), in which the rotations are included as unknowns in the displacement vector. Using GDQR, Liu et al. investigated the free vibration of multispan and stepped Euler beams, and beams carrying an intermediate or end concentrated mass[23]. The GDQR techniques were first applied to both spatial and time dimensions simultaneously as a whole by Wu et al. to study the forced vibration of structural beams [24].

Recently, many studies have been carried out on the mechanical behaviors of FGM beams and plates using DQ method. Wu et al. investigated the dynamic stability of thick functionally graded material plates subjected to aero-thermo mechanical loads [25]. The effects of three-parameter elastic foundations and thermo-mechanical loading on axisymmetric large deflection response of a simply supported annular FGM plate are discussed by Sepahi et al. [26]. Komijani et al. given an analysis of buckling and post-buckling and small amplitude vibrations in the pre/post-buckling regimes of functionally graded beams resting on a nonlinear elastic foundation and subjected to inplane thermal loads [27].

This paper investigates the pull-in instability of fixed FGM micro-beams under a combined action of electrostatic force, temperature change and Casmir force within the framework of von Karman nonlinearity and Euler–Bernoulli beam theory. The temperature-dependency of the effective material properties is specially considered. The nonlinear pull-in results of the micro-beam are obtained by using the DQM. The effects of temperature change, material composition, geometrical nonlinearity and Casimir force are discussed in detail through a parametric study. To the authors' best knowledge, no previous studies which cover all these issues are available.

2. FGM beam model

Fig. 1(a) [15] shows the structure of a typical MEMS device, e.g., a micro-switch, where the key components include a fixed electrode modeled with curved upper face as a ground plane and a movable upper electrode modeled as a FGM micro-beam with length L, width b, and thickness h, separated by a dielectric spacer with an initial gap $g_0(x)$. The origin of the x-coordinate is taken to be the left end of the movable electrode whose deflection is denoted by w. The deflection of the micro-beam is caused by the electrostatic force induced by an applied voltage, intermolecular Casimir force and temperature change.

Without the loss of generality, the curved upper face of the ground electrode is assumed to be a symmetrical second-order polynomial shape [28] in this paper. Hence, the initial gap is expressed as

$$g_0(x) = g_0^*\left[1 + \frac{4(\beta-1)}{L^2}(Lx - x^2)\right], \quad (1)$$

where g_0^* denotes the gap distance at fixed ends $x = 0$ and $x = L$; β is the ground electrode shape parameter characterizing the ground electrode shape; βg_0^* represents the initial gap at the middle point $x = L/2$, see Fig. 1(a). As a special case $\beta = 1$ indicates a flat ground electrode and a uniform initial gap along the beam length see

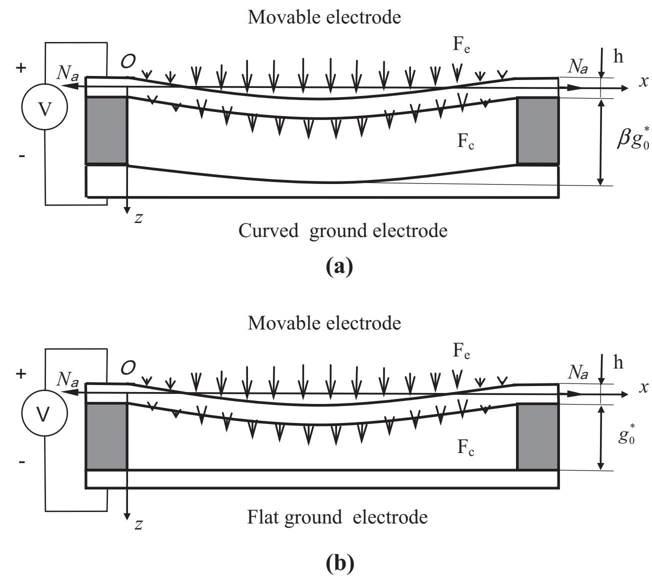

Fig. 1. A beam model for the MEMS device: (a) fixed–fixed micro-beam with curved ground electrode ($\beta > 0$, $\beta \neq 1$); (b) fixed–fixed micro-beam with flat ground electrode ($\beta = 1$).

Fig. 1(b) [16]. The variable ground electrode shape curves with different β are shown in Fig. 2.

The axial force due to the residual strain from the fabrication process is denoted by N_a and is positive for a tensile force, and vice versa. Under the influence of the temperature change and/or the application of a driving voltage V_0, the micro-beam deflects towards the ground electrode under the action of a distributed electrostatic force F_e, Casmir force F_c and/or thermal strain. Both F_e and F_c are nonlinear functions of the gap $g(x) = g_0(x) - w(x)$ between the deformed micro-beam and the ground electrode.

When the voltage increases beyond a critical value, the movable electrode becomes unstable and collapses to the fixed electrode. This phenomenon, known as pull-in instability, is a subject of prime importance in the design of MEMS devices [29]. In this paper, we define the critical temperature variation when the micro-beam collapses only subjected to the temperature change as the "pull-in temperature variation", and the critical voltage corresponding to the micro-beam under the application of V_0 and temperature change as "pull-in voltage". The pull-in deflection denotes the critical deflection when the micro-beam collapses.

Taking into account the first-order fringing field correction, the electric field force per unit length can be written as

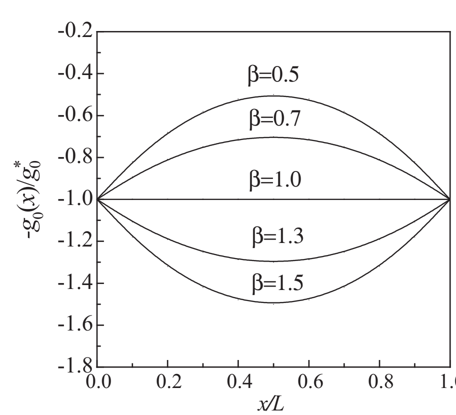

Fig. 2. The ground electrode shape curves for different β.