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Static response and natural frequencies of microbeams actuated by out-of-plane electrostatic fringing-fields

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ABSTRACT

In this paper, we investigate the static behavior of a doubly-clamped microbeam actuated electrically through out-of-plane electrostatic fringing-fields. The resultant actuation force is caused by the asymmetry of the electric fringing-fields. This is designed due to the out-of-plane asymmetry of the beam and its two actuating stationary electrodes. The electric force was estimated by means of fitting the results of the two-dimensional numerical solution of the electrostatic problem using Finite-Element Method (FEM). Then, a reduced-order model (ROM) was derived using the Galerkin decomposition with mode-shapes of a clamped–clamped beam as basis functions. The ROM equations are solved numerically to get the static response of the considered micro-actuator when actuated by a DC load. The results show the possibility of having three different regimes for this particular MEMS device: a bending regime, a catenary regime, and an elastic regime. The eigenvalue problem is then derived and examined to get the variation of the fundamental as well as higher-order natural frequencies when the system is deflected by a DC load. The results show that controlling the microbeam stroke, with a DC voltage on the gate electrodes, enables us to tune the system frequency, resulting in a possibility of a tunable MEMS device without any pull-in scenario.

1. Introduction

Microbeams based structures are the most used building blocks in the micro/nanoelectromechanical systems (MEMS/NEMS) industry. They are frequently used as actuators [1] in triggering the motion of most MEMS devices and as sensors [2] in detecting physical quantities such as acceleration, pressure, small masses, etc.

Electrostatically actuated MEMS devices own high interest in using the electrostatic field as actuation method. Among the numerous electrostatic actuation techniques for MEMS devices, the parallel-plates configuration shown in Fig. 1 is the most reputable and common actuation method because of its easiness and high efficacy [3]. In this method, a movable electrode (the microbeam) is deflected under the effect of an electrostatic load of amplitude V_{DC} applied through a fixed electrode (the gate) (Fig. 1a). Then, the accumulated electric charges generate an electric field which creates an electrostatic force between the charged electrodes. As the electric load increases, the movable electrode deflects and moves towards the stationary one (Fig. 1b). Coulomb forces between the charged plates will make the flexible electrode to deform toward the fixed electrode. This behavior depends non-linearly on the deformation of the upper flexible electrode causing even higher Coulomb forces at higher deformation [4]. If the electrostatic voltage exceeds a certain limit value, this leads to a sudden collapse of the parallel-plates capacitor in which the movable electrode touches abruptly the stationary electrode (Fig. 1c). This happens because the upper electrode's restoring force can no longer resist the contrasting electric force. This mechanical instability occurrence is well-known as *pull-in* stiction instability and the associated voltage is so-called pull-in voltage ($V_{pull\text{-}in}$) [5,6]. A key issue in the design of such parallel-plates electrostatic device is to tune the DC electrostatic load away from the pull-in instability, which leads to the collapse of the microbeam and hence the failure of the micro-device [6]. Several previously published works have addressed the pull-in instability and presented tools to predict its occurrence helping MEMS designers to avoid it [5–12]. These studies, more particularly the pioneering work of Nathanson et al. [5] and Newell [6], investigated this phenomenon under various loading conditions. Such studies considered a resonant gate transistor modeled by a mass-spring system subjected to an electrostatic actuation. They predicted and presented a theoretical justification of the pull-in instability. Previous efforts to numerically determine the effect of fringing-fields on parallel-plates electrostatic actuators must be mentioned duly.

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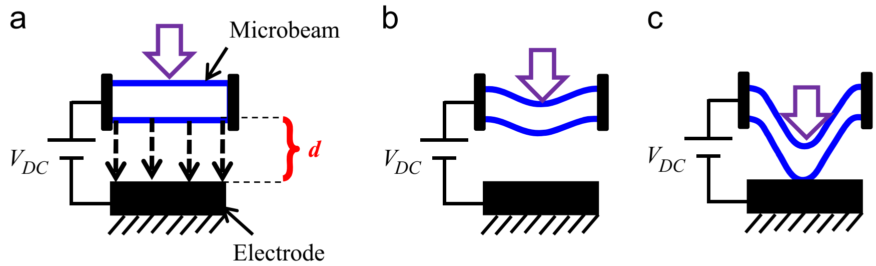

Fig. 1. Parallel-plates DC electrostatic actuation method and the pull-in instability: (a) $V_{DC}=0$ V, (b) 0 V $< V_{DC} < V_{pull\text{-}in}$ and (c) $V_{DC} > V_{pull\text{-}in}$.

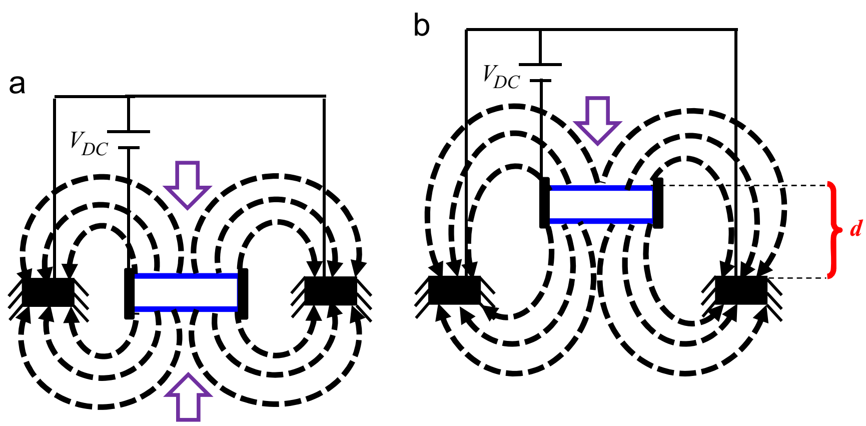

Fig. 2. Fringing-fields electrostatic actuation method. The dashed arrows represent the created electric fields lines for each configuration. The big arrows show the direction of the resultant electrostatic force.

Caruntu et al. [13,14] used the reduced order model method to investigate numerically the non-linear-parametric dynamics of electrostatically actuated MEMS cantilever resonators under a dynamic voltage and while considering the electric fringe effect.

To avoid the pull-in structural instability of the parallel-plates capacitor, comb-drive fingers based actuator was suggested, i.e. in [15,16]. This particular MEMS device produces a constant electrostatic force at a certain applied voltage when the movable comb-drive moves along the direction parallel to the stationary comb-drive fingers. But, with the advantage of low possibility of pull-in, the comb-drive fingers actuator has particularly small displacement (stroke) even with high DC electrostatic load.

From the abovementioned few investigations, one can realize the need of robust MEMS actuator with large range-of-travel (stroke) and without the pull-in instability is of need and of interest. This work presents an innovative type of electrostatic actuator, which could be named fringing-fields based electrostatic actuator, consisting of a movable structure (microbeam) with two stationary electrodes (gates) (Fig. 2). We aim to study the static as well as the eigenvalue problem of such actuator as a potential candidate to replace the classical parallel-plates electrostatic actuator presented and described above by Fig. 1. For this, we propose a clamped–clamped electrically actuated beam consisting two electrodes evenly located at both sides of the beam (Fig. 2). Since the beam and its respective electrodes are assumed to be made of same the sacrificial layer, the resulting electrostatic force will be zero in the configuration corresponding to a beam and both electrodes at the same horizontal plane ($d=0$) (Fig. 2a). Once a vertical distance between the beam and the electrodes ($d>0$) is considered, a distributed resultant electrostatic force, arising from the horizontal asymmetry of the system and hence of the electric fields, acts in the direction opposite to the elevation of the beam and toward the electrodes (Fig. 2b). In this latter configuration which is characterized by the absence of electrodes along the direction of the subsequent beam motion, we expect larger deflections for the beam eliminating any possibility for the pull-in (short-circuit) instability initiation because of the relatively high microbeam stiffness in its lateral direction. Added to all of this, the considered actuator will be less prone to non-linear squeeze-film damping effect, which is usually a principal damping factor in microsensors and resonators actuated by parallel-electrodes. It is worth to mention that these kinds of actuators were widely used as resonant tilting microdevices [16,17]. Non-contact offset slits electrostatic microactuator, was reported and presented in [18–20]. In their proposed devices, a movable slit (mass or microbeam) were located at a certain offset from two stationary slits (electrodes). In [18,19], the authors investigated numerically as well as experimentally the static behavior of a non-contact electrostatic microactuator using slit structures and they observed pull-in and pull-out behaviors depending on the geometry of the microbeam and its respective electrodes. They have found that if the lateral gap between the electrodes and the beam is smaller than a critical value, pull-in still occurs. Whereas in [20], the authors studied theoretically the possibility of using fringing-field electric loads to actuate an initially curved (as well as pre-buckled) microbeam and to examine the possibility of building a bi-stable actuator.

The paper is organized as follows: Modeling information about the fringing-fields electrostatic actuator concept is first presented. Then, the evaluation of the fringing-fields electrostatic force using a Finite-Element Method is discussed. A description of the reduced-order model (ROM) is then described. The static as well as eigenvalue problem of the fringing-fields electrostatic actuator under a DC load are solved and discussed. The last section presents the experimental data and also compares these to the theoretical results of the ROM. The key results of this investigation are finally summarized in the conclusion section.