Journal of Electrostatics 76 (2015) 254–261

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Numerical model for the calculation of the electrostatic force in non-parallel electrodes for MEMS applications

Hassen M. Ouakad

Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals, Dhahran, 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form
11 May 2015
Accepted 1 June 2015
Available online 24 June 2015

Keywords:
MEMS
Actuator
Electrostatic
Non-parallel electrodes
Fringing-fields
FEM

ABSTRACT

In this paper, we investigate the electrical behavior of an electrostatic actuator made of a non-parallel plate's electrodes configuration. The resultant actuation force is caused by the asymmetry of the subsequent electric fringing-fields. This is designed due to the out-of-plane asymmetry of a non-stationary electrode and its two sides actuating stationary electrodes. The electrostatic force is numerically calculated through the results of a two-dimensional numerical solution of the electrostatic problem using Finite-Element Method (FEM). The main objective in this work is to examine the influence of the design parameters on the actuating resultant electrostatic force in this particular arrangement. Four key design parameters were examined: the width and thickness of the electrodes (movable and stationary) as well as the lateral and vertical separation distances between the movable and grounded electrodes. We found out, through several simulations, that both lateral and vertical offsets as well as the electrodes thickness are significant factors in the optimization of the performance of the actuator in such configuration, while the performance seemed to be independent of the electrodes widths. The resultant actuating force level increased with increasing the electrode thickness and with decreasing the electrodes lateral separation distance.

1. Introduction

Electrostatic actuators are the most used structures in microelectomechanical systems (MEMS) including but not limited to microactuators, microsensors, radio frequency filters and optical microdevices. Electrostatically actuated MEMS devices commonly use the electric field as a main and common actuating technique. Among the numerous electrostatic actuation methods for MEMS devices, the parallel-plates configuration as shown in Fig. 1 is the most reliable one because of its effectiveness and lenience in manufacturing [1]. In this technique, the upper and lower electrodes are attracted to each other's under the effect of an applied DC electrostatic load, Fig. 1a. We consider here the simple case of a MEMS actuator relying on this technique, where its upper electrode is movable and its lower electrode is stationary, Fig. 1b. Once the DC voltage is switched "ON", an accumulation of the electric charges on the upper plate generates an electric field which creates an electrostatic force between the parallel-plates. As the applied electrostatic load rises, the upper electrode moves towards the lower one, Fig. 1b. In fact, in this particular configuration, Coulomb forces between the charged plates will make the non-stationary upper plate to be attracted to the lower plate. This phenomenon depends on the deflection of the upper plate causing even higher electric forces at higher deformation [2]. If the applied electric voltage surpasses a certain charge, both plates experience a sudden attraction (collapse) to each other of in which the upper moving plate comes into contact suddenly with the lower stationary plate, Fig. 1c. This occurrence is well-known as the "*pull-in instability*" and the associated DC load is named the pull-in DC voltage [3,4]. A key issue in the design of MEMS devices based on this parallel-plates electrostatic configuration is to tune the electric load far-off the pull-in instability, which leads to the collapse mechanical device [4]. This particular instability, where the electrostatic actuating force overcomes the structure restoring force, is an essential outcome in electrostatically actuated MEMS and it bounds their travel ranges as well as mechanical and electrical performances. Several previously published works have predicted a theoretical justification of the pull-in instability and presented tools to predict its occurrence helping MEMS designers to avoid it [3–10].

Since the stroke is considered to be an important characteristic parameter for micro-actuator, and to avoid such structural

E-mail address: houakad@kfupm.edu.sa.

http://dx.doi.org/10.1016/j.elstat.2015.06.001
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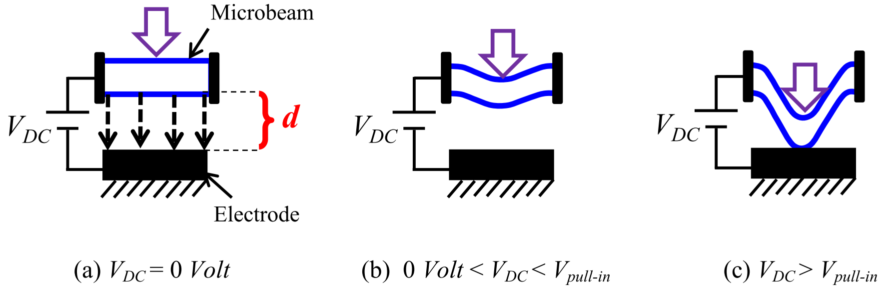

Fig. 1. 1Parallel-plates DC electrostatic actuation method and the pull-in instability.

instability in electrostatic parallel-plates based capacitor, some particular innovative configurations were proposed such as: comb-drive fingers [11–15], sandwich configuration [16], micromirror shape [17], non-parallel plates where the two facing electrodes have a certain trapezoidal profile [18], or even incorporating new features such as additional circuitry, extra intermediate electrodes [19], etc … For example, for the particular design of comb-drive fingers, a constant electrostatic force is realized at a certain applied electric load along the direction parallel to the stationary fingers. But, with the advantage of almost slight possibility of pull-in due to the created constant force, this method showed lower stroke even with high applied forces, something inconvenient for MEMS designers.

From the aforementioned few investigated electrostatic actuating methods, one can realize the serious need of new actuation configurations for electrostatically-actuated MEMS devices optimistically increasing their range of travel and overcoming any possibility of the initiation of the pull-in instability. This effort presents an innovative type of electrostatic actuator, which could be named fringing-fields based electrostatic actuator. This is totally different from the fringing-fields that occur in many parallel-plates electrostatic actuators where the nominal gap between the parallel-electrodes is relatively not negligible compared to the lateral dimensions of the electrodes (thickness and width). Therefore there will be creation of fringing-fields in the neighborhood of the electrodes boundaries which is found to be considerable and must be accounted for when modeling such configuration [20–28].

Our proposed design consists of three electrodes: one movable electrode actuated by two stationary electrodes symmetrically located at its both sides, Fig. 2. We aim to characterize numerically the arising electrostatic force of such actuating electrodes configuration as a potential candidate to replace the classical parallel-plates arrangement as was described previously in Fig. 1. Since all three electrodes are assumed to be made of same the material, the resulting electrostatic force will be zero when all the electrodes are perfectly aligned at the same horizontal plane ($d = 0$), Fig. 2a. Once we start increasing the vertical offset ($d > 0$) between the movable plate and its two corresponding stationary electrodes, 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 movable plate and toward its actuating 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 movable plate eliminating any possibility for short-circuit (pull-in) instability initiation because of the relatively high electrode stiffness in its lateral direction. Large stroke, low damping, simplicity of the structure make this configuration attractive for the MEMS sensors and actuators community.

It is worth to mention that actuators relying on electric fringing-fields were previously used as resonant tilting micro devices [12,29,30] especially for scanning applications, non-contact mode Atomic Force Microscope (AFM) [31], and Scanning Electrostatic Force Microscopy (SEFM) [32]. Non-contact offset slits electrostatic microactuator configuration, where a mobile slit were located at a certain offset from two stationary electrodes, was presented in Refs. [33–36]. These research groups investigated numerically as well as experimentally the static behavior of the proposed 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 Refs. [35], the authors studied theoretically the possibility of using fringing-field electric loads to

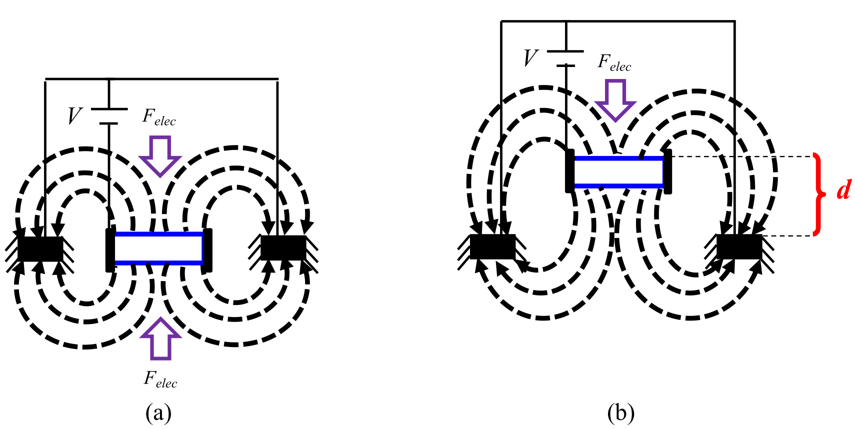

Fig. 2. Fringing-fields electrostatic actuation method. The dashed arrows represent the created electric fields lines for each configuration. The big arrows show the direction of the resultant electrostatic force.