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Analysis of the mechanical behavior of a doubled microbeam configuration under electrostatic actuation

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ABSTRACT

In this paper, the deflection and natural frequency of a doubled microbeam configuration under electrostatic actuation are studied. This configuration consists of a clamped–clamped microbeam while a free–free microbeam is attached to it. The DC electrostatic voltage is applied between the free–free microbeam and the opposite electrode plate. The importance of this model is in its uniform displacement which is useful for microsensor applications. The static deflection, pull-in voltage and natural frequency are studied using three methods of modeling. In the first model, the set of free–free microbeam and the attached segment of clamped–clamped microbeam to it are modeled as a rigid body between two flexible Euler–Bernouli microbeams. The equations of motion and associated continuity conditions are derived using Newton second law. A closed form solution is found for static deflection and vibration about this position. In the second model, the dynamic effect of free–free microbeam is modeled as a concentrated force and moment, and it is introduced by the aid of Dirac function in the motion equation. The equations of motion are solved using Galerkin method. The mode shapes of the clamped–clamped microbeam are employed as comparison functions. The third model is a finite element model using the commercial software, ANSYS. The verification of the solutions is carried out by comparing the results of three considered models and also comparing with previous works. The mechanical behavior of the considered configuration is compared with the mechanical behavior of the single microbeam configuration. The results demonstrate that there is a special geometry for free–free microbeam where the mechanical behavior in both single and doubled microbeam configuration would be approximately the same. This is a useful result, because the doubled microbeam configuration has a uniform displacement which is a main advantage in the design of microsensors.

1. Introduction

Micro electro mechanical systems (MEMS) are known as one of the most important technologies in the 21st century, which can be considered as an attempt to add the mechanical elements into the electric circuits. The main element of many of MEMS devices such as micro-sensors is a movable microbeam and a fixed electrode plate at the opposite side of the microbeam. In these devices a DC potential difference is applied between the microbeam and the electrode plate. The induced electrostatic force deflects the movable microbeam toward the fixed electrode which is called static deflection. In microsensor devices such as pressure sensor, the microbeam moves from its static position to a new situation as soon as the pressure on the microbeam changes. The configuration of the polarized microbeam and the electrode plate is similar to a capacitive system. Thus, an electrical current is induced due to this movement. The induced electrical current is usually used for detecting the quantity of the parameter of the measurement case [1]. By increasing the electrostatic voltage, the mechanical restoring force of the microbeam can no longer resist the opposing electrostatic force, and microbeam is absorbed to the opposite electrode. This voltage which is independent of time or primary location of the microbeam is called static pull-in voltage and leads to the collapse of the structure [2]. In addition, the natural frequency of the microbeam vibration about its static deflection is a criterion for the time of response in these configurations. So, in many works, these parameters have been investigated for a microbeam with rectangular cross section. In several works, the optimization of these parameters has been conducted by change in the geometry of microbeam or geometry of loading. The most important literatures about these researches can be presented as below.

Nayfeh et al. presented a comprehensive theoretical model of the clamped–clamped microbeam under the nonlinear electrostatic actuation that included mid-plain stretching effect. They solved the equation of motion with numerical shooting and Galerkin method [3,4,5]. In several works, the effect of residual

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stress, nonlinear curvature and nonlinear inertia on the pull-in voltage and static deflection of a micro-cantilever have been investigated [6,7,8]. The effect of intermolecular force (Casimir force) and out of plane fringing effect on the mechanical behavior of electrostatically actuated microbeam have been considered in [9,10,11,12]. Rahaeifard et al. [13], Kong [14] and Najar et al. [15] investigated the small scale effect on the pull-in phenomena and static response of a capacitive microactuator subjected to a DC voltage. The effect of increasing or decreasing of the gap size between the midsection of the microbeam and the electrode plate on the static deflection is analyzed using differential quadrature method (DQM) [16]. Abdalla et al. presented a way to increase the pull-in voltage by changing the thickness or width of an electrostatically actuated microbeam [17]. In several works, the static deflection and pull-in voltage of multilayered microbeams have been studied [18,19,20,21]. Jia et al. studied pull-in instability and free vibrations of a microbeam with emphasizing on the effect of ground electrode shape [22]. Ouakad and Younis investigated arc effects in microbeams [23]. Krylov[24] and Zamanian et al. [25] obtained the static behavior of microbeams on which the electrostatic actuating force is partially implemented. Li et al. introduced a nodal model for simulation of electromechanical behavior of doubly-fixed bow-tie shaped microbeam [26]. Joglekar and Pawaskar applied a generic shape optimization framework based on the penalty approach to construct the optimum width profile of an electrostatically actuated microbeam to enhance the pull-in voltage [27,28]. The mechanical behavior of MEMS filter made of two clamped–clamped microbeams coupled by a weak microbeam under electrostatic actuation has been studied by Hammad et al. [29]. Vyas et al. considered a pedal model in which a plate type structure is supported by two beams [30]. Dynamic behavior of a cantilever beam with tip mass subject to an electrostatic excitation has been analyzed in [31,32]. Nayfeh et al. considered the pull-in voltage and natural frequency of a resonant gas sensor made of a rigid microplate electrostatically actuated and attached to the end of the cantilever microbeam [33]. Samaali et al. developed a mathematical model for a RF microswitch made of two electrostatically actuated rigid microplate. They considered that each microplate is attached to the end of a microcantilever [34].

Concisely, in many of previous works, the static deflection, pull-in voltage and natural frequency of a single layer microbeam have been studied [3–12]. The effect of changing the ground electrode shape or the microbeam cross section area on the mechanical behavior of microbeam has been investigated in [16–25]. In several works, the static deflection and pull-in voltage of multilayered microbeam have been studied [26–28]. In some works, the mechanical behavior of microbeam has been investigated by considering the effect of a tip mass or a plate attached to it [29–34]. In all of the above works, the displacement of the system along the length of the microbeam is non-uniform which causes undesirable non-uniform polarizations. For getting a uniform polarization, it has been proposed in [1] that a free–free microbeam with a large thickness needs to be attached to the clamped–clamped microbeam, and the electrostatic actuation must be applied between fixed electrode and the attached part. Although, this model was introduced previously in [1], but its mechanical behavior such as static deflection, pull-in voltage and natural frequency has not been investigated. Here, a theoretical investigation is presented to consider the effect of geometric parameters of the attached part on the static deflection, pull-in voltage and natural frequency of the system. The mechanical behavior of system is compared to the mechanical behavior of a single microbeam configuration studied in previous works. It is shown that there is a special dimension for attached part where the mechanical behavior of considered configuration may be the same as single microbeam configuration. The results of this analysis can be used to design a microsensor or actuator with uniform deflection advantage, where its mechanical behavior is the same to single microbeam configuration with non-uniform deflection.

In this paper firstly the set of free–free microbeam and the attached segment of clamped–clamped microbeam to it are modeled as a rigid body between two flexible microbeams. The equations of motion and associated continuity conditions are derived using Newton second law. Then, a closed form solution is found for static deflection and vibration about this position. Afterwards, another formulation which considers the mechanical effect of the attached part to the clamped–clamped microbeam as a concentrated force and moment on the microbeam is introduced. The concentrated force and moment appear in the equation of motion by the Dirac function, and then the equation of motion is solved using Galerkin method. The mode shapes of the clamped–clamped microbeam are used as the comparison functions. In addition, a finite element model is presented using the commercial software, ANSYS. The accuracy of the results is verified by comparing the results obtained using three mentioned approaches. For special dimension and property, the considered configuration can be considered as an electrostatically actuated rigid microplate attached to the end of a cantilever microbeam. This configuration has been considered in [33]. Therefore, the results of this paper are also verified by a comparison study with the results of the mentioned work. Finally, the formulation of single microbeam under electrostatic actuation is introduced in order to compare its mechanical behavior with the mechanical behavior of doubled microbeam configuration. It is assumed that the electrostatic actuation is applied to a part of the single microbeam that its length is equal to the length of the free–free microbeam.

2. Modeling and formulation

2.1. Modeling 1

The considered configuration which is shown in Fig. 1.a is a doubled clamped–clamped microbeam with length of l. A parallel free–free microbeam has been attached to a part of clamped–clamped microbeam. The left and right ends of this part are

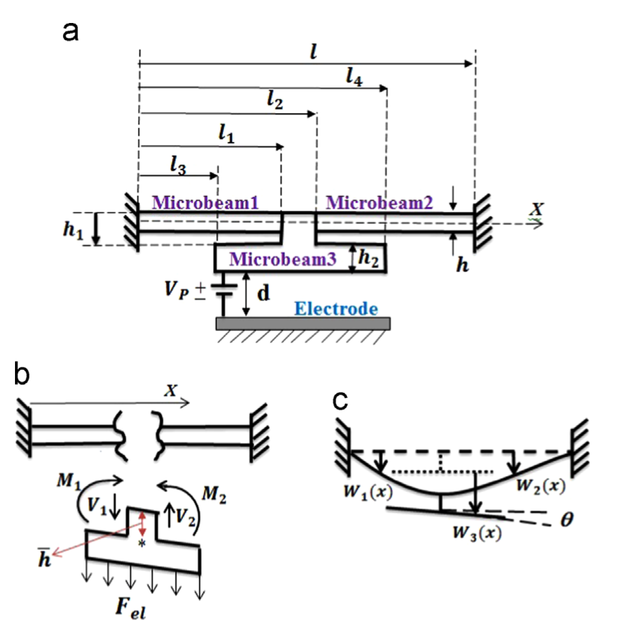

Fig. 1. (a) System model, (b) free body diagram of the ⊥-shaped part after cutting and (c) schematic diagram of microbeam deflection.