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A new analysis of reciprocated beam bending in electrostatic comb drives using a semi-analytical approach

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ABSTRACT

This paper investigates a new modeling and analysis of the voltage induced reciprocated beam bending effects in the unit cell of a planar, variable gap type, capacitive comb drive structures. A semi-analytical approach has been efficiently formulated to solve this coupled electromechanical problem under a steady state condition. The effect of fringe field is also incorporated to improvise on the accuracy of the solution. Additionally, an energy-based method as well as a finite element (FE) based model has been constructed to simulate and validate the semi-analytical approach. The results show that the reciprocated bending of the beams has significant effects on the performance parameters like displacement, capacitance and pull-in characteristics in the comb drive systems. This effect is also seen to vary with applied voltage and stiffness of the combs and springs. Further, a comparison with conventional lumped model shows considerable difference in the estimated values for different parameters indicating a more practical prediction through the proposed approach. Finally, a set of design guidelines is discussed to reduce this bending, so that its effects on the performance of comb drive systems can be minimized.

1. Introduction

Electrostatic comb structures have been for many years, one of the widely used drive configurations for both sensing and actuation in number of microsystems. In general, a set of fixed-free type static beams (combs) are interdigitated with another set of movable combs (attached to a spring suspended shuttle mass) to construct these drives [1]. There exists several drive designs commonly classified based on the direction of movement as lateral, torsional, and longitudinal. They are also classified as symmetric/asymmetric, based on the arrangement of combs on either sides of the shuttle mass [2,3]. Different combinations of these have been tried as per the systems drive requirements and given fabrication technologies [3]. But, with the evolution of Silicon-on-Insulator (SOI) technology, the asymmetric longitudinal/variable gap type drives (as illustrated in Fig. 1) have gained a lot of popularity. Their simplicity in design and ease of implementation into high aspect ratio structures has enabled many applications including high performance accelerometers, gyroscopes, micromirrors, etc. [4–6].

Analysis of different aspects of lateral type symmetric/asymmetric comb drives including electrostatic effects on the design and dynamics of the system have been widely studied [7–11]. Mostly the lumped mass–spring–damper models have been considered for this [7–9]. Also, conventionally the parallel plate approximations for comb movement is assumed in estimating critical parameters like capacitance, pull-in characteristics, etc. [10,11]. Further, at the comb cell level, each of the static combs is assumed to be completely fixed throughout and that the movable combs are ideally rigid, so as to allow only a parallel movement without comb bending during sensing/actuation cycles.

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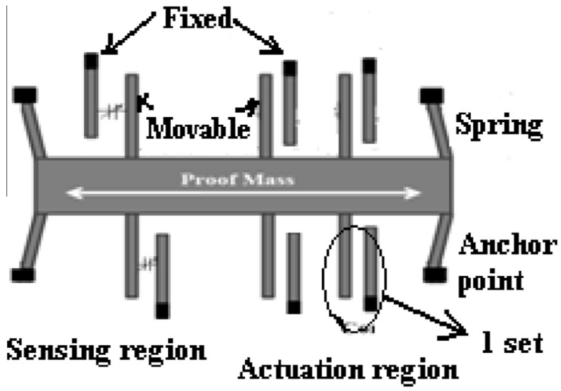

Fig. 1. Illustration of the longitudinal type asymmetric comb drive design.

These considerations may hold true for designing and analysis of some of comb drive configurations. However, at times, because of the use of long, narrow comb structures (mostly dictated by either process or performance requirements), there is a high possibility of combs bending during operation. This leads to a modification of the conventional 'rigid body' assumption for movable combs into a 'flexible beam' capable of bending. Also, because of the removal of spacer layer in structural release step, the static combs as well get released partially, often resulting in a fixed-free type (i.e. instead of conventional consideration as fixed throughout) condition. Therefore, because of these reasons, the effect of bending at the individual comb cell (each unit cell consists of one movable and other fixed-free beam) level requires to be carefully considered for the design and analysis of such drive systems.

One such case was also observed during in-house developmental trials of planar high resolution capacitive accelerometers (i.e. Fig. 2 [12]) fabricated using SOI based MUMPs (Multi-User MEMS Processes) technology from MEMSCAP foundry. Driven by a need for improved sensitivity, yet constrained within the given process/package dictated rule window, the comb lengths of the accelerometer were increased up to 600 μm. So, during operation, whenever a bias voltage was applied, the generated electrostatic force resulted in reciprocated bending of closely placed combs towards each other as shown in Fig. 3(a) and (b). The situation was seen to worsen with increased voltage and gap mismatch between combs in the drive system.

As far as the study of such non-idealities in comb drives are concerned, only side instability issue in the individual combs caused by low off-axis stiffness has been attempted in few literatures [13–17]. Similarly, for electrically actuated single cantilever beam with respect to fixed bottom substrate, thorough analysis have been carried out considering a discrete model [18,19]. Recently, the effects of electrostatic actuation in frequency tunable comb resonators consisting of movable combs in between two completely fixed beams has been analyzed for curved comb contours [20]. A specific case of pull-in stability analysis for two opposing micro-cantilever arrays with different bending rigidities has also been attempted [21]. Nevertheless, a detailed study on the effect of the voltage induced reciprocated beam bending in the unit cell of a differential capacitive type asymmetric, longitudinal comb drive systems does not appear to be well studied.

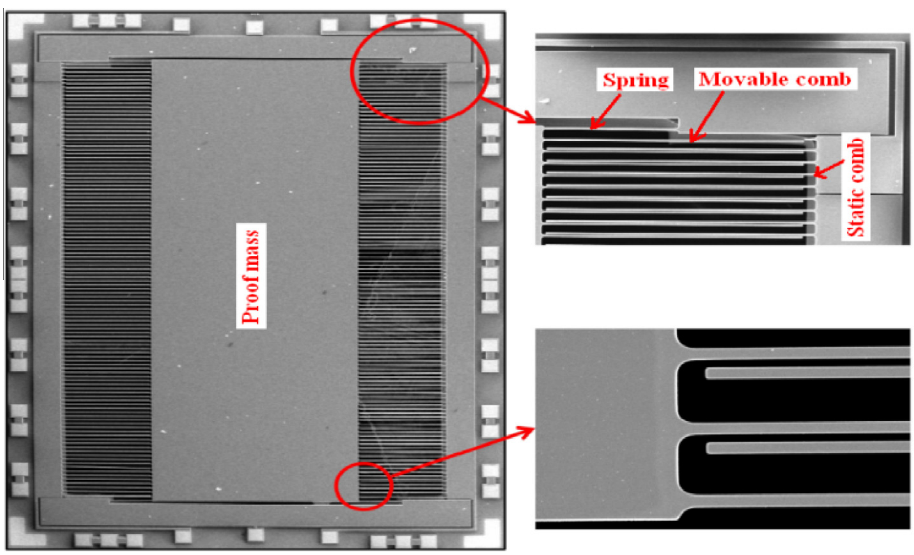

Fig. 2. In-house developed planar SOI accelerometer based on longitudinal asymmetric comb drive design.