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Design and modeling of a novel translational and angular micro-electromechanical accelerometer

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ABSTRACT

A continuous model is presented for a combined translational/angular micro capacitive accelerometer. New design includes two rectangular micro-beams, square shaped proof mass and four pairs of parallel capacitors, which are located in an appropriate construction. In order to find the transverse/torsional vibration effects of micro-beams on the proof mass, the Euler–Bernoulli beam theory is used to derive the governing partial differential equations of the problem which are then solved using modal analysis. Effects of squeeze film on the motion of the proof mass, including both spring and dissipative forces/moments, are considered using nonlinear isothermal Reynold's equation. Afterwards, these equations are solved using HPM method. Electrostatic forces/moments of capacitors are also included in the modeling analysis. Finally, the system of two second-order time-dependent differential equations is obtained. Appropriate formulation in order to correlate the output voltages of the system to the actual input accelerations is presented. Furthermore, output responses are precisely calibrated to form input accelerations. Results for different types of inputs are delineated as five case studies. Apart from transient part of the responses, the model predictions for both angular and translational accelerations show reasonably acceptable convergence with input accelerations of the system. Moreover, results revealed that for various combinations of input accelerations, the system presents reasonably accurate output predictions for each one.

1. Introduction

Today, micro-electromechanical systems (MEMS) technology has revolutionized both real life and industry. For instance, MEMS sensors/actuators such as gyroscopes, accelerometers, seismographs, scanners and pumps have been used in various engineering fields during the last decade. Appropriate and efficient use of MEMS relies on the accurate prediction of their behavior in various application scenarios. Therefore, modeling of MEMS devices as precise as possible seems to be a fundamental step in their design, manufacturing process and application. Among sensors, dynamic response sensors like accelerometers and gyroscopes play an important role in the MEMS industry. Inertial Navigation System (INS), Inertial Reference System (IRS), Inertial Reference Unit (IRU) or Air Data Inertial Reference Unit (ADIRU) are just few examples for the applications of MEMS devices in the aerospace industries [33–35]. These systems use accelerometers and electronic circuitry to provide accurate guidance, navigation, position calculation, speed and acceleration measurement and attitude determination. For instance, on airplanes the flight data recorder uses accelerometers to measure and record acceleration forces on the three axes of the vehicle. Accordingly, these factors are absolutely necessary for the auto pilot operation on the sea and air vehicles. Therefore, accelerometers have wide variety of applications in various industries including maritime and aerospace.

Accordingly, modeling of MEMS devices is of one of the most important steps in their design and application. In the last decade, various theoretical and modeling studies are presented in the open literature [1–9]. However, previous models for a variety of MEMS sensors and actuators include simplified models using lumped formulation. They analyzed different kinds of properties of MEMS devices such as pull-in voltage, dynamic response of torsional micro-mirrors, development of MEMS tunable capacitor with linear capacitance voltage response, mechanical shocks, etc. However, in these simplified models lumped mass assumption seems to be an approximation. For instance, Huang et al. [10] presented a lumped assumption model for a rotating micro-mirror ignoring details like squeeze film damping effect and influence of cantilever mass moments of inertia. Furthermore, Khatami and Rezazadeh [7] have modeled a similar system by adding linear damp-

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ing effect and solved the governing equations using Runge–Kutta method. Caspani et al. [11] have reported the theoretical and experimental characterization of the dynamic behavior of torsional resonators. They modeled the dynamic behavior of the electrostatically actuated torsional resonators both in the linear and nonlinear range. Kouravand [12] modeled some MEMS sensing and actuating mechanisms and proposed an analysis of deflection for micro cantilever besides overlooking the proof mass. Also Linxi et al. [18] studied another micro-accelerometer with grid strip capacitances and sensing gap alterable capacitances. Joshi et al. [19] presented a technique to improve performance of cantilever-type micro-acceleration sensors by optimizing parameters of inertia. Rezazadeh et al. [20] investigated the relationship between input voltage, torsion angle and vertical displacement of the torsional micro-mirror. Comi et al. [21] presented a uniaxial accelerometer based on the stiffness variations of the beams. They considered spring stiffness k and damping coefficient b as an approximation of the effects of the air. Qu et al. [22] presented three-axis capacitive accelerometer with high resolution and robustness. Kim et al. [23] fabricated accelerometer consists of an out-of-plane and in-plane accelerometers which work based on gap-sensitive electrostatic stiffness changing effect. Furthermore, a recent research has been done in this case, presented by Golkaram and Aghdam [24]. In this study only free transverse vibration analysis of thin rectangular plates locally suspended on elastic beam is considered and torsional vibration is not intended. Also, recent investigations have performed a theoretical and experimental study on characterization of resonant micro-accelerometer. For instance, Caspani et al. [25] and Zega et al. [26] have fabricated accelerometers composed of suspended planar proof mass. The system works based on the variation of electric stiffness and, hence, of the frequency.

In this study, a continuous model is presented for a combined angular/translational micro-capacitive accelerometer using two identical suspended beams and a proof mass. In order to provide a model as close as possible to reality, it is tried to include effects of various parameters such as elasticity of deformable beams, squeeze film effects and electrostatic forces/torques exerted by capacitors. The model seems to be the most detailed among other studies with less simplifying assumptions. Although the analysis is presented for particular micro-electromechanical accelerometer, the method, formulation and solution procedure may be utilized for other micro devices such as mirrors and bulk accelerometers. Appropriate formulation is derived to correlate the output voltages of the system to the actual input accelerations. Apart from transient part of the response of the system, the model predictions show good compatibility with input accelerations for various combinations of angular and translational accelerations. In terms of fabrication process, the proposed design does not introduce major complications compared to one micro-beam accelerometer. Micro-fabrication of MEMS accelerometer with four micro-beams has been studied in literature [31,32]. Moreover, other studies suggest accelerometer designs with four resonators and two proof masses [26].

2. Model description

Consider a micro-accelerometer containing two rectangular micro-beams and a square shaped proof mass with schematic views presented in Fig. 1. The proof mass consists of a silicon layer assumed to be rigid and attached to the body of the device by two identical deformable micro-beams. The beams have a rectangular cross section with thickness a, width b and length l. The proof mass has a width of w and thickness t and assumed to be attached to the beams as shown in Fig. 2. Two micro-beams utilized to minimize the pre-deflection of the proof mass. As soon as the structure is subjected to an angular and/or translational input acceleration, the proof mass moves according to the applied acceleration. This leads to differences in the output voltages of capacitors, which may be correlated to the acceleration. Dyadic coupling of eight conductive plates which are attached to the proof mass together with upper and lower stationary plates produces four capacitors. These capacitors are sequentially numbered as C1 to C4 as shown in Fig. 3. It is assumed that normalized stable air pressure is equal to the ambient pressure P_0 and no temperature change occurred during simulation. Furthermore, it is assumed that both angular and translational movements of the proof mass are small enough to keep deformation of the micro-beams in the range of infinitesimal elastic deformation. A schematic deformation of the system during translational and/or angular input acceleration is depicted in Figs. 1 and 2 which are exaggerated for clarity. According to Fig. 3, with-

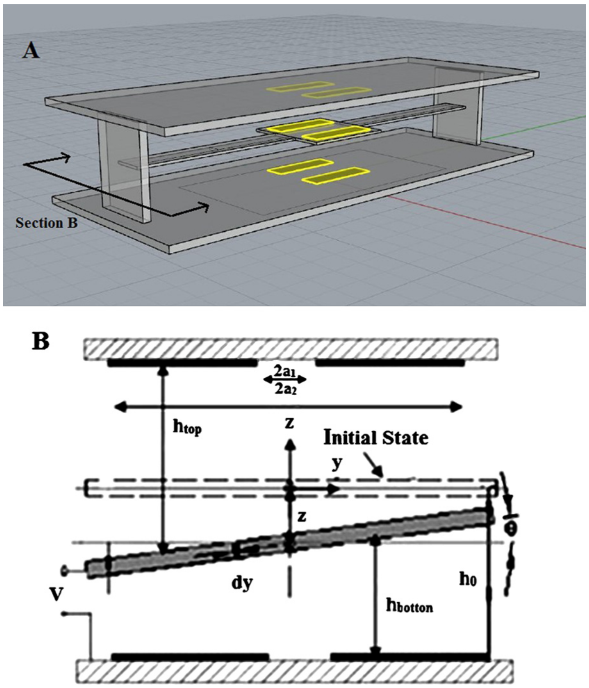

Fig. 1. A) Schematic 3D view, B) Cross-section view of the model.

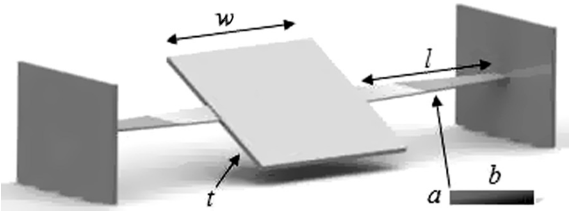

Fig. 2. Schematic 3D view for suspension system.

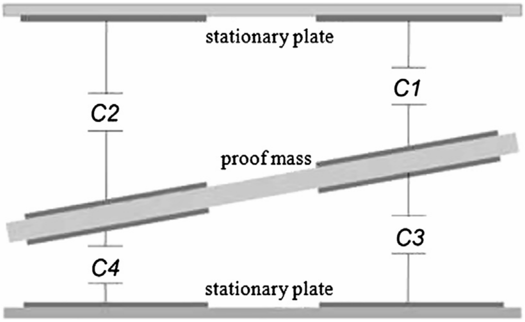

Fig. 3. Identification of capacitances.