Design and Simulation of Silicon-Based Suspension Beams for Various MEMS Sensors

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This paper mainly concentrates on finding maximum displacement and Eigen frequency for microelectromechanical system (MEMS) inertial sensors with various beam structures. In this work, six different shapes of beams are attached with one set of electrodes to find which structure exhibits the maximum displacement with less cross-axis displacement and to observe the operating frequency. The momentum of the beams is directly proportional to the thickness and length, which provides the maximum flexibility to produce momentum on proof mass. The beam thickness is 5 um for all proposed sensors and the momentum has been observed by changing different shapes of beam structures. The momentum occurred on proof mass due to applied physical energy. The same amount of physical energy is applied to all structure and the momentum, quality factor, and displacement are measured which had been compared and the table is given.

1. Introduction

Microelectron mechanical sensors can be used in various miniaturized technologies to determine the physical variable by changing the electrical quantity. Many MEMS sensors are used in industries for automation purpose, and various MEMS-based biosensors are used to determine the physiological variables for the living things. Automation can be created using MEMS structures in automobiles. Change of momentum is an important parameter in the domain of engineering. This measurement consists of the wide range of applications like industrial, medical, military, and consumer applications. The inertial sensor is used for all mentioned problems. An inertial sensor consists of accelerometer and gyroscope, which measures linear and angular displacement forces [1–4].

This paper mainly concentrates on existing sensor parameters which will be useful to design new models. The first important parameter for any inertial sensor is sensing axis; this depends upon the structure of the Beam suspension [2].

The second parameter is the cross-axis displacement; this can be defined when the applied acceleration force is on one axis, but beam bends another axis; this phenomenon is named as cross-axis displacement. This parameter is important parameter for one-dimensional accelerometer, and measurement of displacement is proportional to applied acceleration force on same axis. The displacement of main axis beam in another axis can be named as cross-axis displacement [5–10].

The third parameter is area; effective utilization of area can provide more capacitance. Capacitance is directly proportional to the area; when area increases, capacitances also increase. And the measured capacitance value should be minimum pF which is considerable for any design [11]. Application of inertial sensors can be designed using its natural frequency [12–15]. For example, civil structures constitute the very low natural frequency (Eigen frequency), and mechanical structures constitute the high natural frequency. Depending on application, accelerometer can be designed. Before designing the accelerometer, the
application of accelerometer natural frequency for corresponding applications is defined. As per the maximum momentum and Eigen frequency, we can determine the application of sensor which is suitable for field, and these sensors are mainly utilized for modern technologies where accurate measurement is possible which led to high sensitivity [16].

2. Estimation of Momentum and Eigen Frequency

The momentum of the proof mass is directly proportional to the applied physical force. If the physical force increases on the proof mass, then the momentum of proof mass occurred due to mass and length of the beam. The momentum of the proof mass can be increased with the help of mass and length of the beam. These two are directly proportional to the applied physical force. The angular momentum occurred due to the applied physical force and radius which produced the momentum on angular direction. The second parameter is the Eigen frequency also called as operating frequency which provides the maximum momentum on proof mass at band of frequency that can be called as operating frequency.

2.1. Estimation of Momentum. The momentum on proof mass mainly depends on the three variables; one is mass, second is length of the beam, and last one is the width of the beam. The physical force is directly proportional to the applied force, if the applied force is one direction, and momentum also occurred in the same direction, if momentum is occurred on proof mass as other than applied axis that can be represented as the cross-axis displacement; for one directional sensor, this should be as less as possible. The angular momentum occurred due to the applied physical force and radius which produced the momentum on angular direction.

Linear momentum can be written as

\[ p_l = mv, \]  

(1)

where \( p_l \) is linear momentum, \( m \) is mass, and \( v \) is velocity rigid body.

Linear momentum occurred due to straight beams attached to the proof mass which provides the less cross-axis displacement which is useful to measure the linear momentum using the inertial sensor.

The angular momentum mainly occurred due to radius of the beam which provides flexibility to move proof mass in angular direction, and then angular momentum occurred due to structure of the spring which leads the angular momentum.

Angular momentum can be written as

\[ L_\theta = p_l r, \]  

(2)

where \( L_\theta \) angular momentum, \( p_l \) linear momentum, and \( r \) radius of the rigid body.

Angular momentum occurred due to linear momentum and radius of the rigid body which leads to move the proof mass in angular direction. As per the application of measured momentum, these inertial sensors can be used for linear momentum measurement or angular momentum measurement. Linear and angular momentum is an useful parameter for an inertial sensor.

2.2. Estimation of Eigen Frequency. Eigen frequency which decided the operating frequency which proves mass can vibrate at natural frequency called as natural frequency. The natural frequency mainly depends on the spring constant and mass of the rigid body which can estimate the natural frequency value.

The natural frequency can be written as

\[ f_e = \frac{1}{\pi} \sqrt{\frac{K}{m}}, \]  

(3)

where \( f_e \) is the Eigen frequency, \( K \) is spring constant, and \( m \) is the mass of the rigid body.

The above equation can be useful to calculate the natural frequency of the inertial sensor which decides at which frequency inertial sensor will operate and provide the maximum displacement. The natural frequency decides to depend upon structure of the rigid body and nature of application of inertial sensor. These two parameters play the major role for designing the any MEMS-based inertial sensor to measure the momentum and Eigen frequency which can decide the application.

2.3. Estimation of Quality Factor. Quality factor for MEMS sensors can be defined as ratio of natural frequency to change in band of frequencies. Quality factor can be estimated using the change in frequencies.

\[ QF = \frac{f_e}{\Delta f}, \]  

(4)

where \( QF \) is the quality factor, \( f_e \) is the resonance frequency, and \( \Delta f \) is the band of frequencies. Quality factor for proposed sensors is listed in Table 1.

2.4. SOIMUMS Process. SOIMUMS process is used for the proposed sensor for fabrication, SOIMUMS is a three-layer wafer, bottom layer is a substrate with 400 um, middle layer is an oxide layer with thickness of 1 um, and top layer is device layer with 25 um of thickness. In SOIMUMS process, etching can be done on both sides of the wafer.

3. Design of Inertial Sensor with Different Beam Structures

The proposed inertial sensor consists of the one set of electrodes which is fixed, and another movable called as proof mass which attached with six different structures of suspension beams can determine the momentum of the sensor and can represent the cross-axis displacement.
Figure 1 shows one set of electrodes with two bond pads with 100 um X 100 um. One electrode is fixed, and another electrode is attached with three semisquare-shaped suspension beams; another side of suspension beam is connected to fixed constraints. The momentum of proof mass depends on applied force acting on the proof mass.

The second structure is shown in Figure 2; this is a similar structure, but the beam shape is different. The differential shape can produce the maximum displacement and can measure the cross-axis displacement for the proposed structure. The semicircular shape gives the maximum flexibility to proof mass which produces the maximum displacement; if the beam structure is flexible, high cross-axis displacement can be seen on characteristics.

The remaining structures shown in Figures 3–6 are also same which consist of set of electrodes, but different shapes of suspension beams are connected to achieve maximum momentum with less cross-axis displacement. The area of all six proposed designs is 500 um X 500 um.

### 4. Simulation Results

All six structures were designed and simulated with COMSOL Multiphysics, with electrostatic and solid mechanics physics. Stationery and frequency study has been done to observe the momentum and Eigen frequency for all proposed designs.

The force has been applied X-direction to the proof mass, and force vs. x- and y-axis displacement is plotted. Cross-axis displacement is determined. The operating frequency is observed as 62 kHz for the proposed structure 1 (Figure 7(a)).

The force has been applied on X-direction to the proof mass, and force vs. x- and y-axis displacement is plotted. Cross-axis displacement is determined. The operating frequency is observed as 135 kHz for the proposed structure 1 (Figure 7(b)). The displacement and frequencies are differing along with change of suspension beam structure.

The force has been applied on X-direction to the proof mass, and force vs. x- and y-axis displacement is plotted. Cross-axis displacement is not determined. The operating frequency is observed as 122 kHz for the proposed structure 2 (Figures 8(a) and 8(b)).

The force has been applied on X-direction to the proof mass, and force vs. x- and y-axis displacement is plotted. Cross-axis displacement is not determined. The operating frequency is observed as 122 kHz for the proposed structure 3 (Figures 9(a) and 9(b)).
frequency is observed as 62 kHz for the proposed structure 4 (Figures 10(a) and 10(b)).

The force has been applied on X-direction to the proof mass, and force vs. x- and y-axis displacement is plotted. Cross-axis displacement is determined. The operating frequency is observed as 52 kHz (Figures 11(a) and 11(b)).

The force has been applied on X-direction to the proof mass, and force vs. x- and y-axis displacement is plotted. Cross-axis displacement is determined. The operating frequency is observed as 132 kHz (Figures 12(a) and 12(b)).

Inertial sensor with different beam structures has been simulated along with momentum and frequency analysis that shows simulation result and comparison is tabulated in Table 1. In comparison, various parameters are discussed, and the maximum displacement, cross-axis displacement, and Eigen frequency are found. All design structure areas are same, and beam structure is varied with six different structures which is useful to find the maximum momentum and cross-axis displacement and frequency. The inertial sensor is used to measure the linear and angular displacement along with applied physical force.
Figure 7: (a) Displacement characteristics; (b) natural frequency for the proposed sensor 1.

Figure 8: (a) Displacement characteristics; (b) natural frequency for the proposed sensor 2.
Figure 9: (a) Displacement characteristics; (b) natural frequency for the proposed sensor 3.

Figure 10: (a) Displacement characteristics; (b) natural frequency for the proposed sensor 4.
Six beam structures were designed and simulated with COMSOL Multiphysics software with displacement analysis and frequency analysis. Maximum displacement is observed for all proposed structures, and the cross-axis displacement is measured. The Eigen frequency is observed for all proposed designs. Finally, comparison is done with maximum momentum, cross-axis displacement, and Eigen frequency. The proposed design with square shape achieved maximum displacement for high acceleration force applications.

**Data Availability**

The data used to support the findings of this study are included within the article.

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**Figure 11:** (a) Displacement characteristics; (b) natural frequency for the proposed sensor 5.

**Figure 12:** (a) Displacement characteristics; (b) natural frequency for the proposed sensor 6.
Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


