Simulation of a Dual Axis MEMS Seismometer for Building Monitoring System

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Abstract: A dual axis microelectromechanical–system (MEMS) seismometer targeted for building monitoring system during earthquake has been simulated for a full scale of ±5g acceleration. The design uses the capacitive effect for vibration sensing. This comb drive capacitive MEMS seismometer consists of 8 springs with two proof masses. The device is very low cross axis sensitive (almost negligible cross axis error). The cross axis sensitivities of X-axis are 0.001% and 0.00009% towards Y- and Z-axes respectively, while the Y-axis cross axis sensitivities towards X-axis is 0.000005% and Z-axis is 0.0001% when maximum input acceleration of 5g is applied. COMSOL Multiphysics (V. 5.0) has been used to compute the eigenfrequencies and static responses of the device. Von-mises stresses were applied at X- and Y-axes for the estimations of fracture in the springs under 5g acceleration. From simulation results, the displacement sensitivities of X-axis=0.114µm/g and Y-axis=0.204µm/g while capacitive sensitivities of X-axis=0.551pF/g and Y-axis= 0.346pF/g were calculated.

Keywords: MEMS Seismometer, Accelerometer, Cross axis sensitivity, COMSOL Multiphysics, Earthquake.

1. Introduction

Sensing of acceleration is the common principle of accelerometer. Capacitive, piezoresistive, piezoelectric etc. are the different principles used to find the acceleration. In all these mechanisms, the capacitive technique is attractive for the researchers now a days due to its high sensitivity, low noise floor, better temperature performance, low-power dissipation and a simple structure [1]. Different MEMS accelerometers were designed for their specific applications. By knowing the resonant frequencies and high or low-g accelerations, the application of the device can be determined. For example, an accelerometer used in navigation and missile intelligence has a very high operating resonant frequency and gravitational (g) acceleration [2], [3]. In another case, the required operating resonant frequency and g-acceleration of the accelerometer is low for the earthquake detection and health monitoring applications [4-6]. Accelerometer that is used to measure the ground motion during earthquake is called a seismometer.

MEMS seismometers are used in earthquake studies and are designed to be highly sensitive to ground vibrations. Low noise, high sensitivity and a dynamic range in-between 100 to 140 dB makes a MEMS seismometer and the current best MEMS accelerometers [7].

This paper presents a very low cross axis sensitive MEMS acceleration seismometer used to measure the building vibration induced by the earthquake. The design has the ability to adjust extra capacitive finger structures inside the proof mass, which can lead the sensor to be highly sensitive. The analysis and calculations from the simulation results showing its application of sensing building vibration. The sensor uses capacitive effect. COMSOL Mulitphysics (V.5) has been used to analyze the resonant frequencies and static responses of the sensor. The rest of our paper is as follows: Section 2 presents structural analysis and use of COMSOL Multiphysics while section 3 represents simulation and results of the proposed design and finally the paper is concluded in Section 4.

2. Structural Analysis and Use of COMSOL Multiphysics

Two designs were evaluated in order to get a final desired design. The first design with a crab leg and the second one with a folded springs on X-axis were simulated and compared the cross axis errors. After finite-element method (FEM) simulations using COMSOL Multiphysics, the second design was selected on the basis of their low cross axis sensitivities (almost negligible) and desired resonant frequencies. The crab leg and folded springs were simulated and evaluated by applying force on X-direction and checking the deformation on Y-direction. Folded spring was found to be low deformed towards Y-direction, as shown in Figure 1. The selected design was then also simulated with the different widths of the springs. The optimum value of 4 µm was selected due to their best performance. Table 1 shows the compared cross axis errors of two designs with different springs while Table 2 represents the final design with different widths of the springs.

Table 1: Cross Axis Errors of the Design with Two Different Types of springs

Type of spring	Cross axis sensitivities (%)
	X (towards Y)
Crab leg	0.01
Folded	0.001

Table 2: Cross Axis Errors of the Final Design with Different Widths of the springs.

Spring width (µm)	Cross axis sensitivity (%)	
	X (towards Y)	Y(towards X)
3.9	1.9×10^{-3}	5.2×10^{-6}
4	1.1×10^{-3}	5.2×10^{-6}
4.1	4.2×10^{-3}	1.6×10^{-3}

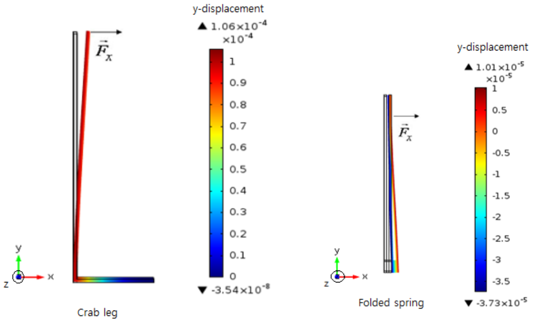
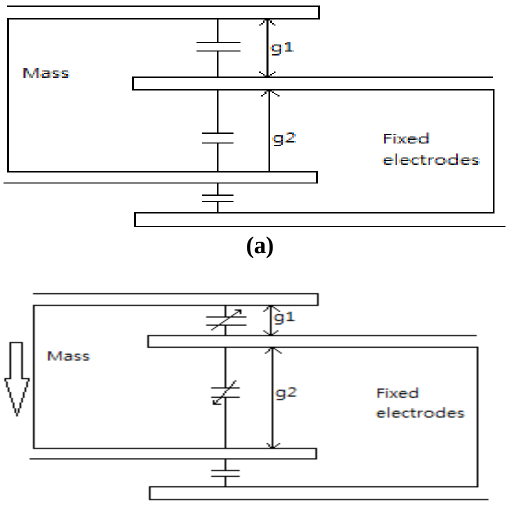


Figure 1. Springs submitted to a force in X-direction; colors show the deformation in Y-direction.

The final selected design consists of a pendulum like structure composed of two proof masses and 8 springs. The springs were fixed at their ends. This mass spring system obeys the classical spring equation (ma=k.x), where ‘k’ is spring constant in N/m, ‘x’ is the deflection of spring, ‘m’ is the mass in kg and ‘a’ is acceleration in m/s^2. As the device is subjected to acceleration (g) in ‘X’ or ‘Y’ direction, the proof mass and movable electrodes move along the direction of body forces. Due to this motion, the gap between the movable and fixed electrodes will change, as shown in Figure 2. The sensing scheme is based on the variable gap capacitance. The variation in capacitance against input acceleration is then converted to voltage output using a differential amplifier circuit. This output is further amplified and processed to obtain the final output from the seismometer.

The sensitivity of the seismometer can be defined as the change in capacitance (ΔC) per unit acceleration (g), which is ΔC/g. Substituting for all the parameters from the analytical calculations, the value of sensitivities in terms of ΔC/g are 0.551pF/g (X-axis) and 0.346pF/g (Y-axis). The change in capacitance has been calculated which is shown in Table 3.



(a)

(b)

Figure 2. Representation of fixed electrode and the proof mass electrode. **(a)** Before and **(b)** after movement of the mass in downward direction.

Table 3: The change in capacitance on 1 to 5g acceleration.

Acceleration (g)	Change in X-axis capacitance (ΔCx). (pF)	Change in Y-axis capacitance (ΔCy). (pF)
1	0.551	0.346
2	1.152	0.71
3	1.703	1.057
4	2.254	1.404
5	2.855	1.768

The final selected design is shown in Figure 3 where the schematic of the proposed dual axis-seismometer are as under: From (1) to (4) are X-axis springs and from (5) to (8) are Y-axis springs.

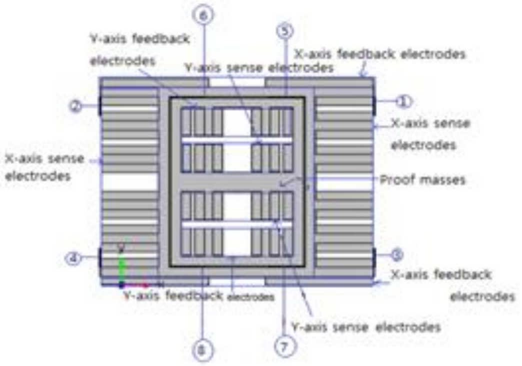


Figure 3. Schematic and operating principle of the proposed dual axis-seismometer.

3. Simulation and Results

For mechanical analysis, the design was simulated using COMSOL Multiphysics to investigate the mode shapes, deflections, and cross axis sensitivities. COMSOL Multiphysics is one of the important simulation platform in the fields of science and engineering. It is being widely used as a simulation tool for electrochemical, mechanical, and fluid flow applications. It has been reported in various studies [8-10] that COMSOL Multiphysics can give accurate results with high confidence for developing customized solutions.

In study 1, the first six resonant modes were analyzed. The first two eigenfrequencies of Y- and X-axes were 1106.2 Hz and 1480.8 Hz, respectively. The two modes of interest are shown in Figure 4.

Study 2 illustrates the normal operation of a seismometer by applying the input acceleration from -5 to 5g and computing the resulting displacement of the proof mass. The input acceleration is simulated as a load vector in two directions. The proof mass deflections are 0.57 µm (X-axis) and 1.02 µm (Y-axis), when a maximum input acceleration of 5g is applied to the proof mass. Table 4 summarizes the displacements of proof mass at 0-5g input accelerations (g) while Figure 5 shows the linear relationship between the displacement and the applied input acceleration.

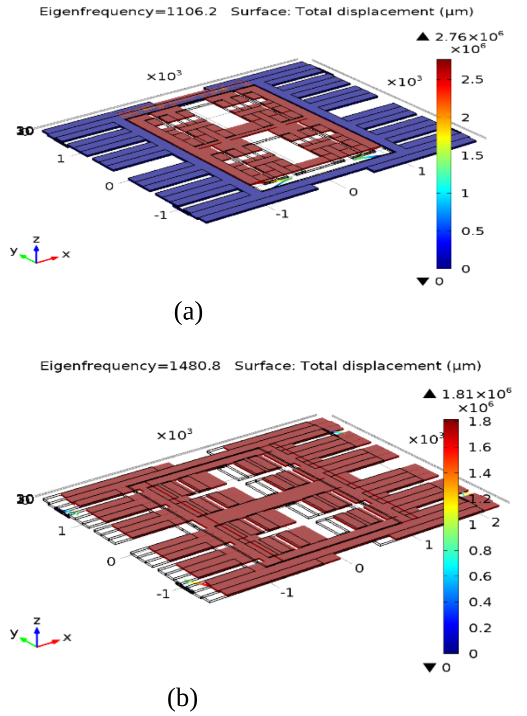
The proposed design is very low cross-axis sensitive (almost negligible). Cross-axis sensitivity is a measure of how much output is seen on one axis when acceleration is applied on a different axis, typically specified as a percentage. The coupling between two axes results from a combination of alignment errors, and circuit crosstalk. The cross-axis sensitivity is measured by dividing the acceleration response in a given direction by the response in the main designed direction as in Equations (1) and (2).

$$S_{xcross} = \left(\frac{S_{xy}}{S_x}\right) \times 100 \qquad (1)$$

$$S_{ycross} = \left(\frac{S_{yx}}{S_y}\right) \times 100 \qquad (2)$$

Equations 1 and 2 show the cross axis errors of X- and Y-axes towards Y- and X-axes respectively. This cross-axis errors should be less than 0.1 % in seismometers. Minimum cross-axis sensitivity indicated a good sensor design. Measurement results show that the deflection is very low towards other direction when a maximum input acceleration of 5g is applied in the main direction. The cross-axis sensitivities of the proposed seismometer have been summarized in Figure 6.

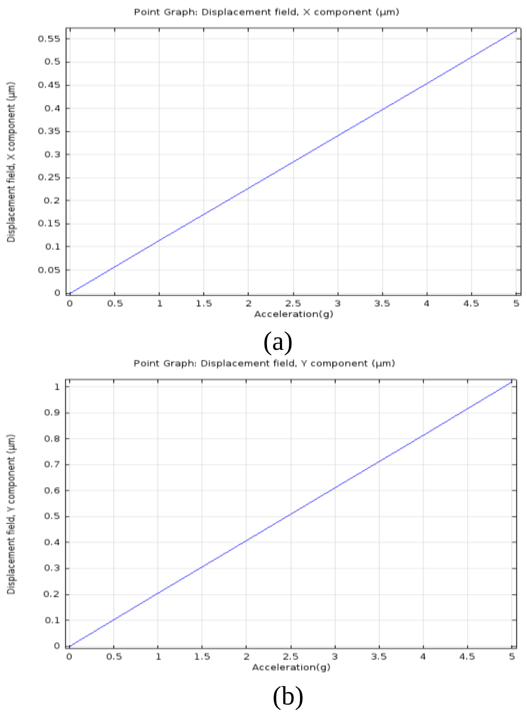
In the proposed seismometer, the material used for the springs is silicon single crystal. All the springs were carefully designed to prevent it from fracture. The device will be of no more use if any of spring is broken during the operation. Von mises stress is used to check whether the silicon springs will withstand a given maximum load condition. Figure 7 shows the von mises stress occurs at the ends of every X- and Y-axes springs when a maximum acceleration of 5g is applied. The maximum stresses were 7.19 MPa and 4.88 MPa at X- and Y-axes springs, respectively. Since fracture stress for single crystal silicon is 7 G Pa, the result shows that device is able to survive under a 5g applied acceleration is both X and Y directions.



(a)

(b)

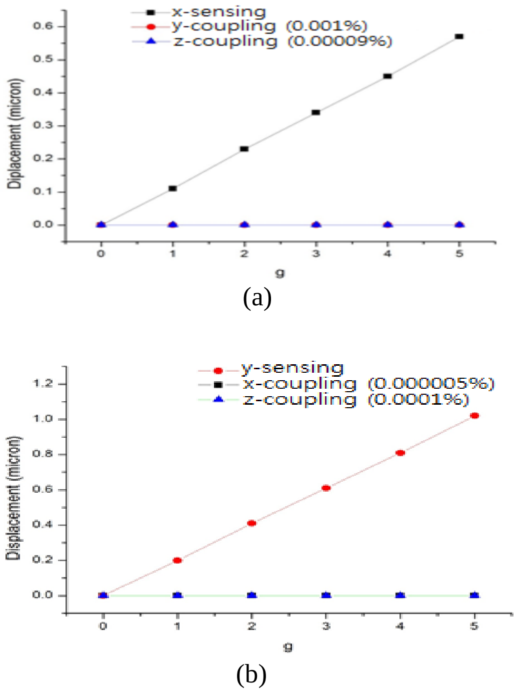
Fig. 4. The Eigenfrequency simulation results for the desired modes (a) Y-axis and, (b) X-axis.



(a)

(b)

Fig. 5. Displacement vs acceleration. (a) X-axis and, (b) Y-axis.



(a)

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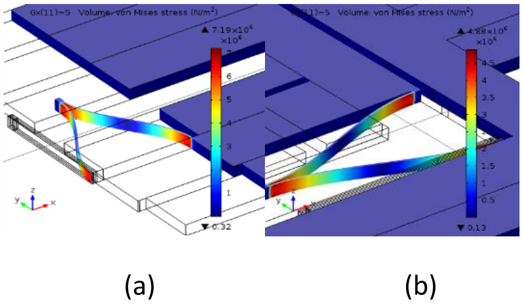
Fig. 6. Cross-axis sensitivity of, (a) X-axis towards Y- and Z-axes, and (b) Y-axis towards X- and Z-axes.



(a) (b)

Fig. 7. Von-mises stresses at the ends of springs, (a) X-axis, and (b) Y-axis. The applied acceleration is 5g.

Table 4: Displacements of X- and Y-axes at 0-5g.

Acceleration (g)	Displacement (µm)	
	X-axis	Y-axis
0	0	0
1	0.11	0.2
2	0.23	0.41
3	0.34	0.61
4	0.45	0.81
5	0.57	1.02

4. CONCLUSION

In this paper, a very low cross-axis sensitivity dual axis MEMS capacitive seismometer design was proposed for a specific application of sensing building vibration during an earthquake. FEM based simulations were performed in COMSOL Multiphysics (V.5). Two designs with different types of springs and their widths has been simulated for the desired eigenfrequencies and static responses. The capacitive sensitivities for x-axis and y-axis are 0.551Pf/g and 0.346Pf/g, respectively. Moreover, the sensor has a linear relationship between displacement and targeted input acceleration range of 5g. Higher sensitivities can be achieved due to the design capability of adjusting extra capacitive finger structures. All the final parameters has been summarized in Table 5.

Table 5: Parameters of the proposed seismometer.

Parameters	Seismometer	
	Y-axis	X-axis
Full Scale Range (g)	5	5
Spring stiffness	5.7437 N/m	18.8694 N/m
Resonant Frequency	1106.2 Hz	1480.8 Hz
Quality factor (assumed)	100	100
Mechanical Brownian Noise	0.31 µg/sq(Hz)	0.27 µg/sq(Hz)
Dynamic range	124 dB	125 dB
Static sensitivity	0.346 pF/g	0.551 pF/g
Static sensing capacitance	3.467 pF	10.02 pF
Sensing Gap Distance	2 µm	2 µm
Thickness of Proof mass	30 µm	30 µm
Number of Comb fingers	420	1180

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