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3D MEMS Accelerometer–Design Optimization and Performance Analysis

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Abstract—*An optimized design of a micro-electro-mechanical system (MEMS) three dimensional accelerometer for sensing applications is proposed and demonstrated. The serpentine springs in the structure allows a large diaphragm structure to be suspended with a designed air gap, effectively suppressing unwanted deflection. The proposed device design has been studied and further elaborated and corrected using COMSOL Multiphysics. The device design is stable and is capable of being utilized for various applications. For the purpose of introducing this design, it is demonstrated in the capacity of a motion sensor here which is capable of sensing in x-, y-, and z-directions.*

Keywords*: micro-electro-mechanical system (MEMS) accelerometer, serpentine spring, motion sensor, COMSOL Multiphysics.*

1. INTRODUCTION

The success of the microelectronic fabrication industry has led to the birth of Micro-Electro-Mechanical-Systems (MEMS) which has revolutionized the field of sensors and actuators [1]. MEMS accelerometers are used as motion sensors as they sense the acceleration experienced by a system [2]. These devices have countless applications in various fields including defense, industry, health care and consumer appliances. Some of the many common applications are in consumer product industry such as cell phones, laptops, digital cameras and advanced robotics [3]. Motion sensing is becoming increasingly important with the advances in technology [4]. In healthcare, they are used to measure a person's activity and thus prove useful in detection of metabolic syndromes, seizures by monitoring heart rates [1], blood pressure, temperature, brain activity and physical activity [5].

The MEMS device structure proposed here responds to the stimulus (force, pressure etc.) through somehow altering its structure. This design comprehends all three directions of motion by using a serpentine spring system suspending a proof mass. The design presented in this paper is validated using COMSOL Multiphysics.

2. DEVICE DESIGN

Accelerometer operates by measuring the inertial force generated when a mass is accelerated. The force applied deflects the suspension of the proof mass. So, if the deflection of the structure can be measured, the acceleration can be easily determined. This accelerometer structure consists of a mass-spring-damper system which is used to interact with the inertia forces. The Fig. 1 shows the final mechanical design in 3D.

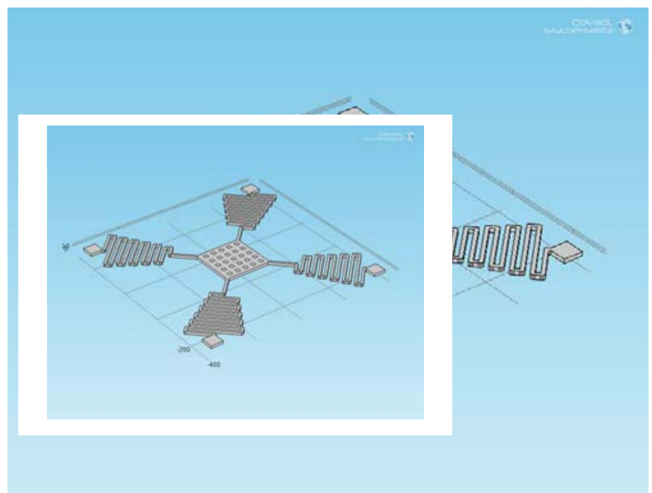

Fig. 1: Proposed design in 3D.

The structure is created using 2D geometrical workplane in COMSOL. After the initial design, Finite Element Analysis (FEA) is implemented using physics models in the COMSOL Multiphysics software.

Simulation result is shown in Fig. 2 which shows the displacement of the structure. The colored legend describes the response at different points.

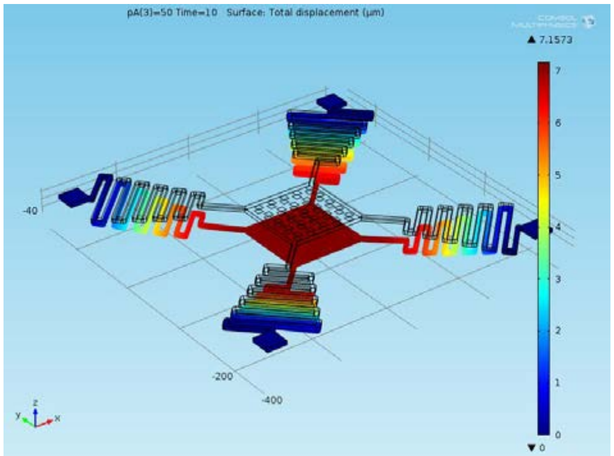

Fig. 2: Structure after simulation.

This design has the capability of multi-axis sensing, out of plane detection: rotation and has high shock survivability.

3. PERFORMANCE ANALYSIS OF THE DEVICE

The seismic mass deflects under inertial force that the application of acceleration 'a_d' produces. The displacement sensitivity of the device is defined as the displacement of the movable mass per unit gravity acceleration g (1g =9.8 m/s^2) along device sensitive direction [2]. The four meandering springs are connected in parallel.

Assume the width and length of the central proof mass is 'W_{ma}' and 'L_{ma}', respectively. The thickness of the device is 't'. The density ρ and Young's modulus E of silicon material are as follows:

The density of silicon is ρ= 2330 kg/m^3

Young's modulus of silicon is E= 1.65 × 10^{11} Pa

For a smaller deflection angle i.e. $\theta_{da}< 5^\circ$, the accelerometer can be identified as a simplified spring-mass model. If the total sensing mass of the model is M_{as} and and the applied acceleration along the downward direction as 'a_d', then the inertial force experienced by the sensing mass i.e. F_i can be given as

$$F_i = -M_{as} \times a_d \quad - (1)$$

The displacement x_{as} of the movable mass with the total spring constant of the spring 'K_{ss}' is calculated as

$$x = \frac{F_i}{K_{ss}} = -\frac{M_{as}a_d}{K_{ss}} \quad - (2)$$

The resonant frequency of the, f_0, of the spring-mass system is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_{ss}}{M_{as}}} \quad - (3)$$

The nominal capacitance of the device can be easily calculated as it behaves like a parallel plate capacitor

$$C = \frac{\in.A}{d_0} \quad - (4)$$

Therefore,

$$C_1 = \frac{\in.t.L_{ma}}{d_0} \quad - (5)$$

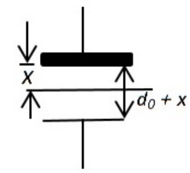

Fig. 3: Differential capacitance distance depiction.

Assume that there is downwards vertical acceleration, the movable mass experiences an inertial force upwards by x, as shown in Figure 3. Assuming that that the deflection is small ($x << d_0$), the capacitance changes to

$$C_2 = \frac{\in.t.L_{ma}}{d_0 + x} = \frac{\in.t.L_{ma}}{d_0\left(1+\frac{x}{d_0}\right)} \approx \frac{\in.t.L_{ma}}{d_0}\left(1 - \frac{x}{d_0}\right) - (6)$$

$$\Delta C = C_1 - C_2 = \frac{\in.t.L_{ma}}{d_0}\left(\frac{x}{d_0}\right) = C_1\left(\frac{x}{d_0}\right) \quad - (7)$$

From equations (7) and (2), it is deduced that the differential capacitance change ΔC of the accelerometer is directly proportional to the experienced acceleration a_d. Thus, the acceleration can be measured by measuring the differential capacitance.

The seismic mass, M_{as}, of the accelerometer can be expressed as

$$M_{as} = \rho t(W_{ma}L_{ma}) \quad - (8)$$

And the spring constant K_{as} of one section of suspended spring is

$$K_{ss} = \frac{12\,E\,I_{ss}}{L_{ss}^3} \quad - (9)$$

Where I_{ss} is the inertial momentum of the spring and is given by

$$I_{ss} = \frac{W_{ss}t^3}{12} \quad - (10)$$

Four suspended springs are connected in parallel and have the same size. Thus, the total spring constant K_t of the device is given by

$$K_t = K_{ss1} + K_{ss2} + K_{ss3} + K_{ss4} \quad - (11)$$

$$K_t = 4K_{ss1} = 4 \times \frac{4 \times 12 \times E \times I_{ss}}{L_{ss}^3}$$

$$K_t = \frac{4 \times E \times W_{ss}t^3}{L_{ss}^3} \quad - (12)$$

Now, the sensitivity of the displacement of the device along the desired direction can be expressed as

$$S_{dm} = \frac{M_{as}g}{K_t} = \frac{\rho t(W_{ma}L_{ma})L_{ss}^3 g}{4EW_{ss}t^3} \quad - (13)$$

From the above equation it can be concluded that the sensitivity S_{dm} is directly proportional to the width & length of the seismic mass and third power of the spring length and is inversely proportional to the thickness.

4. CONCLUSION AND FUTURE WORK

In this paper, a simplified spring-mass model is used to calculate the sensitivity of the device and its relation to various other parameters like spring length, seismic mass surface area, thickness of the device, etc. Simulation results concur with the theoretical analysis. In practical applications, by adjusting the device parameters the desired sensitivity can be achieved.

The future work is to further increase the device sensitivity by way of increasing the seismic mass and reducing further its spring constant. Fabrication of the device and further improvement of the proposed design is the ultimate goal.

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