Investigation of the Effects of Geometrical Parameters on Sensitivity of Capacitive MEMS Accelerometer

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Abstract: MEMS technology is rapidly taking an important role in todays and future sensor systems. MEMS are able to lower the device size from millimeter to micrometer and maintain and sometimes surpass the performance of conventional devices. In this paper design of a two-axis capacitive accelerometer is described. A finite element analysis method is used to perform the simulation of the Accelerometer under various operating conditions and to determine the optimum configuration. Variation of capacitance of the device with applied acceleration as well as sensitivity of the device is analyzed. From the analysis results, a capacitive MEMS accelerometer with enhanced sensitivity has been proposed. The sensitivity of the accelerometer has efficiently been enhanced. The effects of geometrical parameters of the Accelerometer were analyzed.
Keywords: MEMS; capacitive accelerometer; sensitivity; finite element analysis.

1 INTRODUCTION

During last decades, MEMS (Micro-Electro Mechanical Systems) technology has been rapidly and successfully developed in achieving miniaturized mechanical structures and their integration with microelectronic components. Acceleration sensors have been amongst the first implemented MEMS products [1-3]. The MEMS device design optimization is becoming an interesting and important research issue. Recently, various efforts on MEMS device design optimization have been made and published [4-14]. The MEMS accelerometers usually consist of a proof mass suspended using an elastic element (spring). When the device is accelerated, an inertial force is applied to the proof mass, resulting in its deflection in the direction opposite to the applied acceleration [7]. The acceleration can be extracted from the measurement of the capacitance between suspension element and electrode stress in the suspension elements. The simulation of MEMS based capacitive accelerometer is done by using ANSYS software [15].

Among many MEMS applications, capacitive detection is known to offer several benefits compared to other sensing methods, especially due their ease of implementation. Capacitive methods do not require integration of a special material, which makes them compatible with almost any fabrication process. They also provide good DC response and noise performance, high sensitivity, low drift, and low temperature sensitivity.

Therefore, in this paper the general concept, main design of the MEMS based capacitive accelerometer is modelled and simulated.

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2 SENSING STRUCTURE

A schematic structure of the capacitive accelerometer is shown in Fig. 1. All upper capacitors are wired parallel for an overall capacitance C1 and likewise all lower ones for overall Capacitance C2, Otherwise capacitance difference would be negligible to detect. The MEMS Accelerometer is composed of movable proof mass with plates that is attached through a mechanical suspension system to a reference frame, movable plates and fixed plates represents capacitors. The deflection of proof mass is measured using capacitance difference.

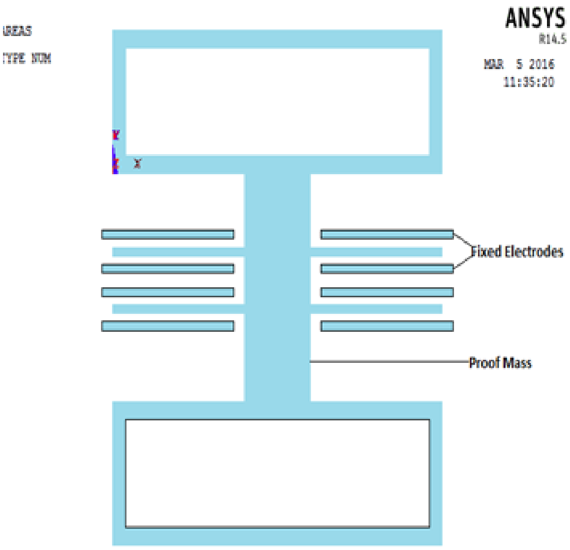

Fig. 1. Schematic diagram of capacitive accelerometer.

3 MODELLING AND ANALYSIS

3.1 Mathematical Model

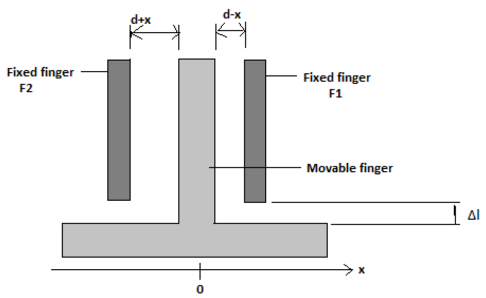

Fig. 2. Differential capacitance of MEMS accelerometer.

Assume for each section of the folded-beam, the beam width and length is W_b and L_b respectively. The width and length of central proof mass are considered as W_m and L_m respectively. The device thickness (thickness of the poly-silicon layer) is h and there is N_f totally sensing finger groups. For each movable finger, the finger width and length are W_f and L_f separately. When there is no acceleration, the capacitance gap between each movable finger and its left/right fixed fingers is d.

Considering that the length not covered with mobile finger is null ($\Delta l_f = 0$) as shown in Fig. 2. The static sensing capacitance of the MEMS comb accelerometer when there is no acceleration (a = 0) is:

$$C_0 = \frac{\varepsilon_0 N_f L_f h}{d} \quad (1)$$

When there is acceleration ($a \neq 0$) along horizontal direction, the movable mass experiences an inertial force toward right by x (Fig. 2). The value of capacitances C_1 and C_2 are changed to:

$$C_1 = \frac{\varepsilon_0 N_f L_f h}{d}\left(1 - \frac{X}{d}\right) \approx \frac{\varepsilon_0 N_f L_f h}{d}\left(1 - \frac{X}{d}\right) \quad (2)$$

$$C_2 = \frac{\varepsilon_0 N_f L_f h}{d - X}\left(1 + \frac{X}{d}\right) \approx \frac{\varepsilon_0 N_f L_f h}{d}\left(1 + \frac{X}{d}\right) \quad (3)$$

The differential capacitance change

$$\Delta C = C_1 - C_2 = \frac{2.\varepsilon_0.N_f.L_f.h}{d}\left(\frac{X}{d}\right) \quad (4)$$

Assume the total sensing mass of the accelerometer as m, the inertial force $F_{intertial}$ experience by the sensing mass for acceleration *an* along sensitive direction is:

$$F_{inertial} = -ma \quad (5)$$

Taking total spring constant of the beams as K, the displacement x of the movable mass can be calculated as:

$$X = \frac{F_{inertial}}{K} = \frac{ma}{K} \quad (6)$$

3.2 Sensitivity Analysis

From Eq. (6), the displacement of the device along the sensitive direction can be expressed as [14]:

$$X = \frac{ma}{K} = \frac{\rho.h.a(W_m.L_m + N_f.W_f.L_f)L_b^3}{2.E.W_b^3} \quad (7)$$

And the displacement sensitivity S_d becomes:

$$S_d = \frac{\rho.h(W_m.L_m + N_f.W_f.L_f)L_b^3}{2.E.W_b^3} \quad (8)$$

Given a displacement of the movable mass and fingers where x is much smaller than the static capacitance gap d and ΔL_f much lower ($\Delta L_f \approx 0$), the capacitance sensitivity S_c can be expressed

$$S_C = \frac{2.N_f.\varepsilon_0.h.(L_f - \Delta L_f)}{d^2} S_d \quad (9)$$

The capacitance sensitivity S_c is given

$$S_C = \frac{2.N_f.\varepsilon_0.h.L_f}{d^2} X \quad (10)$$

$$S_C = \frac{2.N_f.\varepsilon_0.h.L_f}{d^2} \cdot \frac{ma}{K} \quad (11)$$

The different geometrical parameters used in this simulation is given in Table 1. The various displacement of moving mass is achieved by applying various accelerations such as 0 g, 10 g, 20 g, 30 g, 40 g and 50 g etc. The displacements of proof mass along y-axis is simulated and measured by the ANSYS software.

3.3 Output Voltage

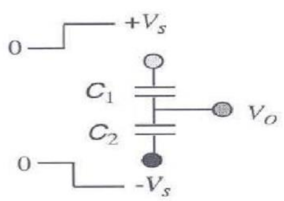

Fig. 3. Equivalent electrical circuit of Accelerometer.

It could be easily shown that the output voltage (V_{out}) of the circuit in Fig. 3 was given by:

$$V_{out} = -V_s + \frac{C_1}{C_1 + C_2}[V_s - (-V_s)] = \frac{C_1 - C_2}{C_1 + C_2} V_s \quad (12)$$

The capacitances $C_1$and C_2were not fixed due to the motion of the electrodes attached to the proof mass. When the moveable electrodes were at rest position, the two capacitances were equal and the output voltage was zero. When acceleration is applied the movable electrodes displaced and the gaps between fixed and movable electrodes will change by amount of ∂x. Thus, the output voltage as a function of displacement (∂x), original gap (d) and input voltage magnitude (V_s) were given by

$$V_{out} = \frac{C_1 - C_2}{C_1 + C_2} V_s = \frac{\frac{\varepsilon A}{d_1} - \frac{\varepsilon A}{d_2}}{\frac{\varepsilon A}{d_1} + \frac{\varepsilon A}{d_2}} V_s = \frac{d_2 - d_1}{d_2 + d_1} V_s = \frac{\partial x}{d} V_s \quad (13)$$

4 RESULTS AND DISCUSSIONS

The aim of the simulation using the finite element method is to obtain the characteristic properties of the modeled system. Finite element method can determine the impact of different parameters on the device characteristics if they are included in the model.

The different geometrical parameters used in this simulation are given in Table 1. The various displacement of moving mass is achieved by applying various accelerations such as 0 g, 10 g, 20 g, 30 g, 40 g and 50 g etc. The displacements of proof mass along y-axis is simulated and measured by the ANSYS software.

Table 1. Physical and geometrical parameters of a model.

Parameters	**Design**
Capacitance gap (d)	2µm
Device Thickness (h)	5.2 µm
Mass Width (Wm)	34 µm
Mass Length (Lm)	812 µm
Beam Width (Wb)	6 µm
Beam Length (Lb)	150 µm
Finger Width (Wf)	34 µm
Finger Length (Lf)	120 µm
Number of Fingers (Nf)	136 µm
Young's modulus of poly-si (E)	1.72×10^{11} pa
The Dielectric constant of air	8.854×10^{-12} F/m
The Density of poly-si (ρ)	2330kg/m^3
Gravity Acceleration (g)	$9.8 m/s^2$
Total mass (m)	2.81×10^{-10} kg
Spring Constant (K)	1.13×10^{2} N/m

4.1 Mechanical Analysis

Displacement of the proof mass has been measured using ANSYS software. The capacitance and sensitivity of the device has been calculated using MATLAB software. Some parameters like beam width and beam length is also varied. The simulated results have been plotted as shown below.

One capacitance (C1) increases linearly and another value of capacitance (C2) decreases linearly with the increasing values of acceleration. The variation of the values of both capacitances with respect to acceleration is shown in Fig. 4.

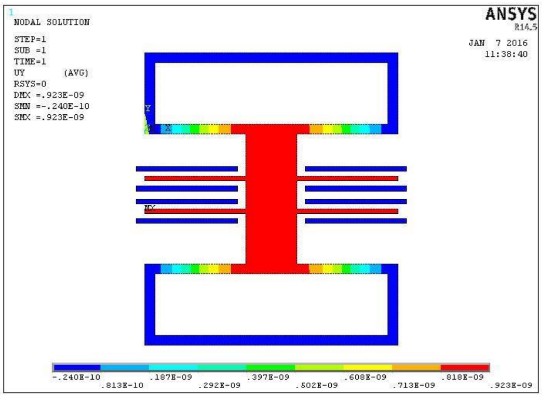

Fig. 4. Capacitances vs. Acceleration of moving mass.

When Acceleration is applied proof mass is displaced from its original position. Depending the value of displacement the capacitances are also changed. The relation between capacitances and displacement are shown in Equations (2) and (3). The various displacement of moving mass is achieved by applying various accelerations such as 0 g, 10 g, 20 g, 30 g, 40 g and 50 g. One those simulated displacement profiles are shown in Fig. 5.

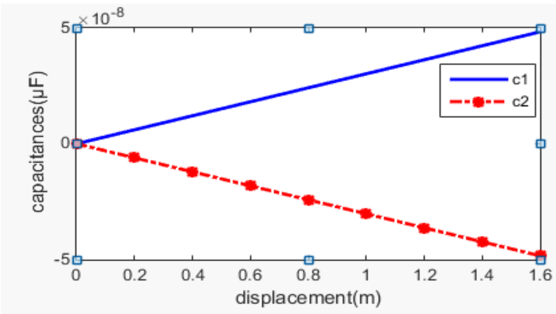

Fig. 5. Displacement along y-direction for 10g force using ANSYS.

The aim of steady-state analysis is to determine the characteristics function of the sensing member. The sensing of acceleration consists of two value conversions, the first is the conversion of acceleration to displacement, second is the conversion of displacement to capacitance difference.

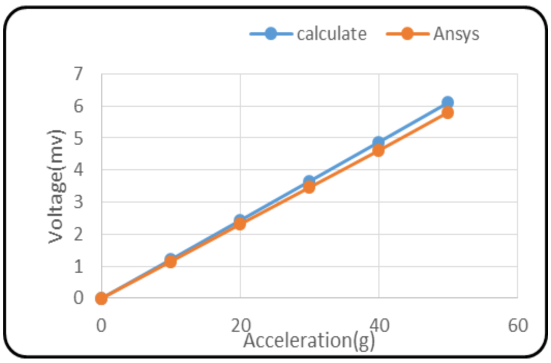

Fig. 6. - Comparison of calculated and simulated Voltages.

The calculated result of displacements and simulated results of displacement after applying acceleration is plotted in the Fig. 6.

4.2 Electrostatic Analysis

Simulated and calculated results of capacitances versus acceleration is shown in the Figs. 7 and 8 respectively.

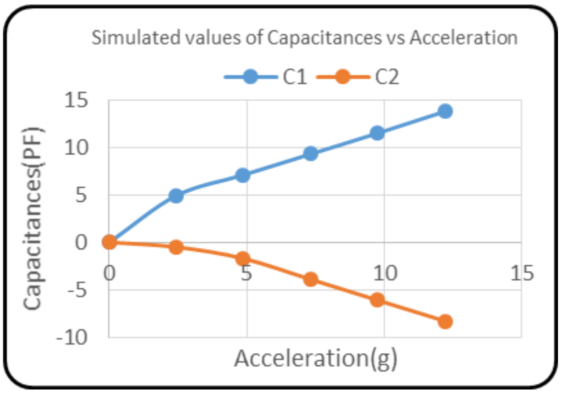

Fig. 7. Simulated values of capacitances in Ansys software.

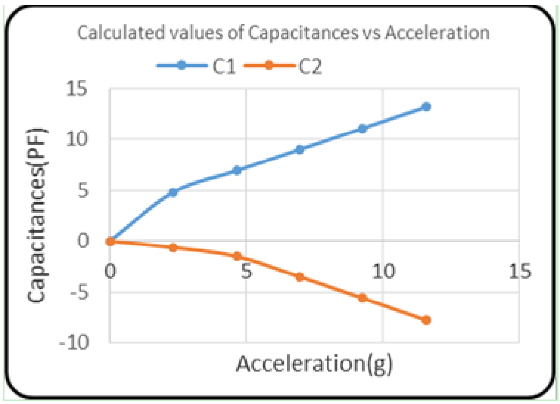

Fig. 8. Calculated values of capacitances.

From Figs. 7 and 8, it is observed that output capacitance C1 increase with increase in acceleration and C2 decrease with increase in acceleration.

To achieve better performance of the device, its sensitivity must be improved. Therefore, to obtain a better sensitivity of a capacitive accelerometer, it is very important to have proper beam width and beam length. The sensitivity has been calculated from Equation (8). The variation of sensitivity with respect to beam width and beam length has been plotted in Figs. 9 and 10. From Figs. 9 and 10, it is observed that sensitivity of the device increase with higher beam length and thinner beam width.

5 CONCLUSIONS

A comparative study is made for the analytical and FEA results for the proposed device structure. Finite element analysis software ANSYS is used to

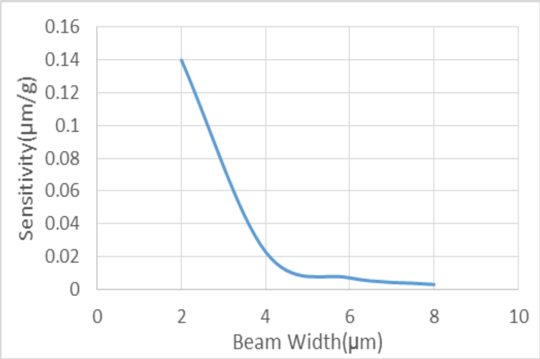

Fig. 9. Variation of Sensitivity with the variation of Beam Width.

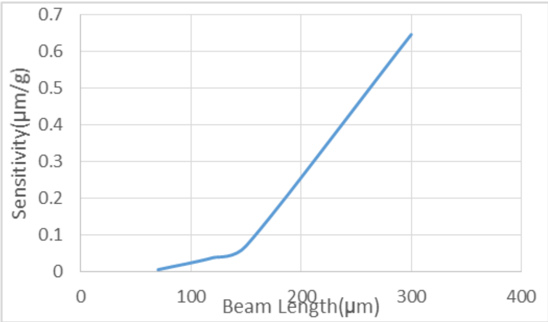

Fig. 10. Variation of Sensitivity with the variation of Beam Length.

simulate the proposed MEMS based Capacitive Accelerometer. Analytical model is simulated using MATLAB. Displacement of proof mass with respect to given acceleration is measured and the corresponding changes of capacitances are calculated. Variation of Capacitance and sensitivity against the beam length and beam width of the device is also analyzed in detail. It has been noted that sensitivity of the device increases with increase in beam length and reduction in beam width.

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