Parametric Study of Micro Electro-Mechanical System Capacitive Type Accelerometer

Mr. Avinash B. Shinde[1], Mr. A. A. Panchwadkar[2]

[1]*ME Design PG Student, PCCOE*
[2]*Associate Professor, PCCOE*

Abstract - *Micro-Electro Mechanical Systems are widely used for measuring the acceleration because they are small in size and less in weight. In this paper effort was done on the study of different parameters such as beam length and beam width of capacitive MEMS accelerometer and their effects on the change in differential capacitance. A 2D model of accelerometer was prepared and the modal analysis was performed on model to find the mode shapes of moving finger. In modal analysis 100 numbers of modes were extracted with frequency range 0 to 1000 Hz. and mode shapes were found out. The deformation of moving finger for extracted modes is observed. Among them at frequency 230.80 Hz and 792.31 Hz finger showed deformation along acceleration measuring axis. At these frequencies, the effect of deformation of finger on capacitance value was analyze.*

Key Words: Capacitive type MEMS, Sensitivity, Modal Analysis, Resonant Frequencies

1. INTRODUCTION

To measures the acceleration, different types of accelerometer are available as piezoelectric and piezoresistive and MEMS capacitive type accelerometer. Among them MEMS are used widely because they are small in size and weight as compared to piezoresistive and piezoelectric accelerometer. Currently they are used in automobiles to set the correct time for air bag deployment. Micro Electro-Mechanical System (MEMS) were firstly developed in 90's century. Capacitive type woks on the principle of capacitance change in parallel plates. Capacitance change is directly depending upon the distance between plates and area of plates. Acceleration is sensed by mass and causes the change in the distances of the plates and ultimately the capacitance. This capacitance is ultimately used to measure the acceleration. Force is applied on the mass due to acceleration sensed by device is determines by Newton's second law of motion. To analyse the displacement of mass of accelerometer, it can be compare to equivalent model of mass, spring, damper system.

1.1 Working of MEMS Accelerometer

Accelerometer is a device used to measure the acceleration or decelerations of device. Works on the Newton's second law of motion which states that force applied by anybody is equal to product of mass of body and acceleration of body. This force on the mass makes it to displace from mean position. This displacement is proportional to the acceleration of device. Fingers are attached to the mass.. Fingers moves with mass and the distance between moving finger and fixed finger changes. It changes the capacitance in fingers which is used to measure the acceleration

1.2 The broad objectives of the study are

1. To study the working principle of capacitive MEMS accelerometer
2. To study the effect on capacitance change for variable distance between two plates due to deformation occurs in moving finger and find the error in measurements of capacitance

The current need of the manufacturing industry in the any machine development consist of various factors such as vibration analysis, balancing the masses of rotating machines. Vibration of machine leads to failure of machine parts. Therefor accurate result should be shown by vibration sensors such as accelerometer which is used to find the magnitude of acceleration of machine with respect to time.

2. LITERATURE

The sensitivity of the device is desirable parameter while designing a transducer. Most of the work done before have kept their focus on the increasing the sensitivity of device by optimizing the device parameters.

Zakriya Mohammed et al [1] focus their work on optimizing the gap between moving and fixed finger. As the gap between moving and fixed finger directly affect the change in capacitance between them. The designs utilize a simplified comb structure to detect capacitance change between moving and fixed fingers. By finding the optimum gap the device is designed to get the high capacitance which is the function of displacement of proof mass. They found that there is critical anti-gap spacing at which the device shows the highest sensitivity. The main focus of their work was to achieve high-sensitivity while keeping the device dimension as small as possible. A complete parametric study was performed to calculate the optimum design values. The key parameters which were carefully studied are the total mass, spring constant, the finger length, and the anti-gap spacing. The spring constant is varied by changing the beam length and width.

Yi Ma et al [2] work on the parameters of the flexible beam. As the length and width of flexible beam directly affect the stiffness of beam and ultimately the displacement of the proof mass. They conducted their work by taking the flexible element as a cantilever beam and optimize design for beam as its length and width is found. They found that the performance of capacitive accelerometer with cantilever beam is highly depending on the length, width and thickness of beam. The beam design optimization has performed, and the optimized design parameters have achieved, including beam length 500um, beam width 600um, and beam thickness 6um. By increasing the length of beam, sensitivity of accelerometer can increased but there are limitations to increase the length up to certain level. Because beyond limit if the length is increased the sensitivity of device become over sensitive and may damage the structure of the accelerometer. Results also show the effect of beam design on the resolution, which is the minimum and maximum acceleration the accelerometer, can sense.

Keya Sanyal et al [3] from their paper they have shown the variation of capacitance change and sensitivity with respect to the length and width of the beam. Sensitivity and capacitance change both these term are related to each other. To increase the sensitivity of accelerometer there should be more change in capacitance change for certain acceleration sensed. They analyzed the variation of capacitance change of the device with applied acceleration, and also analyzed the sensitivity of the device. The performance analysis of the device is done using ANSYS Multiphysics software. For simulation purpose a 2D model is prepared using the ANSYS software and the displacement of the proof mass is measured from the deformed structure.

Meftah Hrairi et al [4] focused their work on Finite Element Analysis of MEMS accelerometer and they in additionally they also consider the effect of temperature on the device performance. The temperature of accelerometer was varied from 100C to 500C and the displacement was measured to check whether the temperature has any impact on the displacement. From the result, it is found that as the temperature increases the displacement also increases. However, the displacement is very small.

Table-1: PHYSICAL AND GEOMETRICAL PARAMETERS[3]

Parameters	**Value**
Capacitance gap (d)	2 µm
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 Length (Lf)	120 µm
Young's modulus of poly-si (E)	1.72*10^11 Pa
The Dielectric constant of air (ε)	$8.854*10^{-12}$ F/m
The Density of poly-si (ρ)	2330 kg/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

3. WORKING PRINCIPLE OF ACCELEROMETER

Capacitive type Micro Electro-Mechanical System accelerometer is equivalent to single degree of freedom spring, mass and damper system. It consists of spring mass which is attached to the spring which is here beam element. And also the damping effect occurs in the gap between moving and stationery finger.

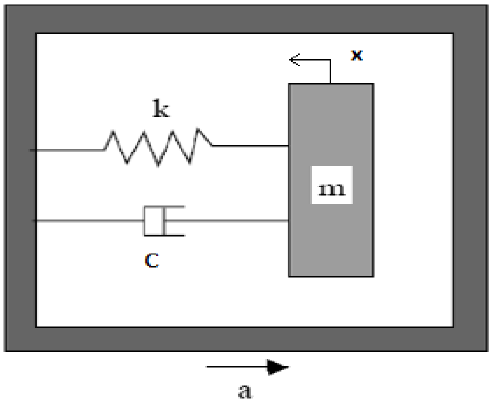

Fig 1: Mass-Spring-Damper System [6]

According to Newton's second law force applied on the system when the mass (m) subjected to the acceleration (a) is

$$F_{applied} = ma_{applied} \quad \text{....... ....(1)}$$

The proof mass is attached to the spring which get extended or compressed depend on the direction of applied acceleration on the mass. Which causing the mass to displace by amount x. Resisting force apply by the spring is :

$$F_{spring} = kx \quad \text{..(2)}$$

There is also a damping effect (c) in the system which affects the performance of the accelerometer. The damping is due to air damping between stationery and moving fingers, which resist the movement of the proof-mass. The damping force can be defined as :

$$F_{damping} = c\dot{x} \quad \text{...(3)}$$

Now according to the second law the relation between is that the sum of all forces acting on proof mass is equal to inertia force on proof mass :

$$F_{applied} - F_{spring} - F_{damping} = m\ddot{x} \quad \text{.................(4)}$$

Finally, the motion of the spring mass damper system as a function of the applied acceleration is given by:

$$m\ddot{x} + c\dot{x} + kx = F_{applied} = maapplied \quad \text{.. ....(5)}$$

This equation can be used to analyses the system. Where natural frequency of the system is:

$$\omega n = \sqrt{\frac{k}{m}} \quad \text{.....(6)}$$

The movement of the proof mass gives a change in capacitance between the movable finger attached to the proof mass and the fixed finger attached to the structure. In this method, the acceleration can sense by measuring the changes of capacitance. When acceleration is applied in the X-direction, the proof mass gets displaced and the finger gap spacing of fingers changes. At one side, the capacitance increases while it decreases at the other with same acceleration

3.1. Capacitance calculation

The capacitance when the mass is at its mean position and which is same in both sides

$$C0 = \frac{\mathcal{E} N_f L_f h}{d} \quad \text{.....(7)}$$

When mass displace and move by the distance x the value of capacitance will be

$$C1(x) = \frac{\mathcal{E} N_f L_f h}{d-x} \quad \text{.....8)}$$

and

$$C2(x) = \frac{\mathcal{E} N_f L_f h}{d+x} \quad \text{.....(9)}$$

The differential capacitance change is

$$\blacktriangle C = C2 - C1. \quad \text{.....(10)}$$

4. ACCELEROMETER MODEL

Magnitude of capacitance measured by single pair of fixed and moving finger is very low. So for further processing the measured capacitance for getting acceleration value, sufficient value of capacitance magnitude should get from fingers.

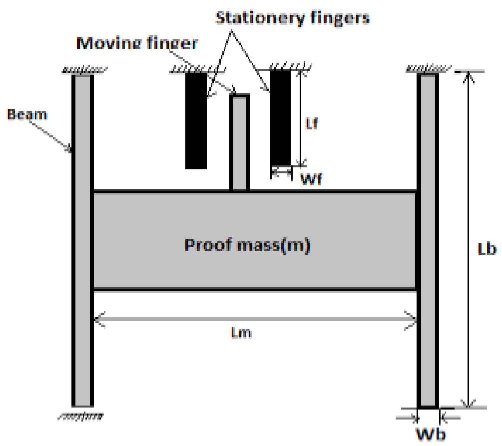

Fig 2: MEMS with one pair of fixed and moving finger

To get the higher value of capacitance multiple finger pairs are added in series with finger as shown. But for simplification only one finger pair is considered. Simplified diagram of capacitive accelerometer is shown in figure 2. Similar model is prepared on ANSYS to analyses the behaviour of system. The thickness of finger and mass is varied and the displacement of the finger is observed. As a part of simulation, a 2D model is prepared using ANSYS and the displacement of the finger is observed from the deformed structure.

When acceleration is applied, proof mass displaced from its original position. Depending on value of displacement, the capacitances are also changed. The relation between capacitances and displacement has shown in equation 8 and equation 9 of changed capacitance

5. MODAL ANALYSIS

Bandwidth of device is the frequency range over which the device can take the readings. Higher the bandwidth of the device means better is the device because one device with large bandwidth can be used for various applications. To find the bandwidth of the device the mode shapes and resonant frequencies are need to be known.

The model of accelerometer with single finger attached to mass is prepared in ANSYS software and modal analysis is done to find the mode shapes and resonant frequencies. In modal analysis, 100 numbers of modes have extracted with frequency range 0 to 1000 Hz. and mode shapes have found. The thickness of mass and finger is varied from 3 μm to 6.5 μm. The effect of thickness on the resonant frequency is found. The graphs of thickness verses resonant frequencies are plot. A graph shows that change in thickness of finger does not much affect the resonant frequency of finger. But at resonant frequencies the moving finger is not parallel to the fixed finger and the distance between them is not same along length. Due this change in distance the capacitance between fingers will be changed and the acceleration shown will be different than the actual value

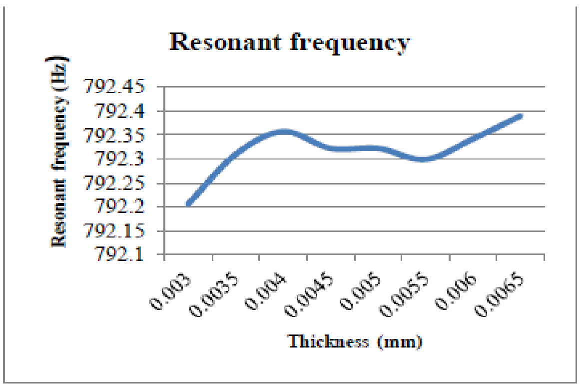

Fig 3 : Thickness Vs Resonant frequencies of moving finger.

The mode shapes have found from the software and among them first mode of finger found at node number 21 with frequency 230.802 Hz and second mode found at node number 40 with frequency 792.312 Hz. Difference between two mode shapes is found as 562 Hz which is determined as bandwidth of the accelerometer.

Decreasing the thickness value of finger shows same bandwidth so that the size of the device can reduced but due to reduced thickness, area between fingers decreases and reduces the capacitance value

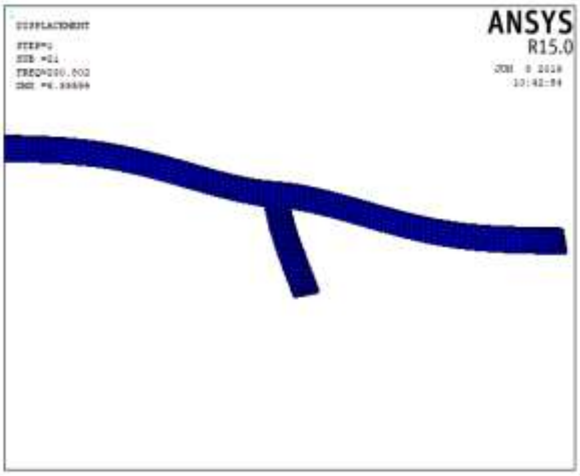

Fig 4: Deformed shape of finger at 230.802 Hz

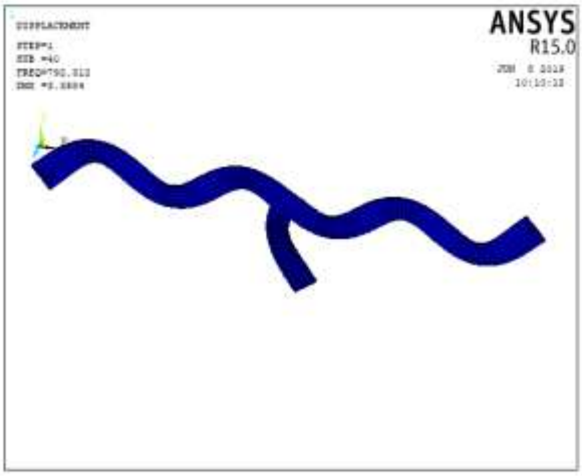

Fig 5: Deformed shape of finger at 792.312 Hz

As the capacitance value is directly depend upon the area of plates. Therefor decreasing thickness will decrease the area and ultimately the capacitance.

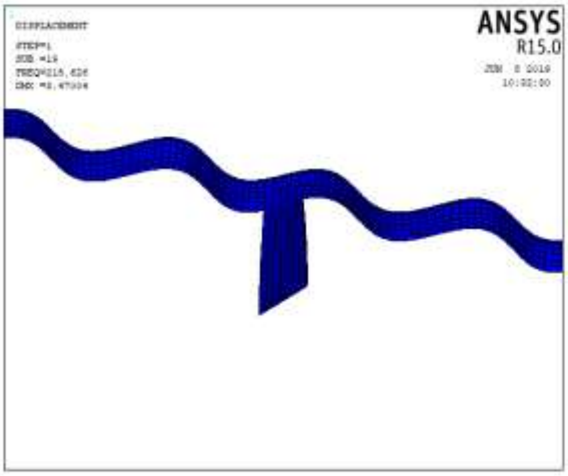

Fig 6: Deformed shape of finger at 215.626 Hz

If we consider at particular acceleration the finger and mass moved with the distance 1 μm. The difference between actual value of differential capacitance and the capacitance measured by the devices found are found out

Table 1: Error in differential capacitance due to deformation in finger

Sr. No.	**Frequency (Hz)**	**▲C (pF) for parallel fingers**	**▲C (pF) for deformed fingers**	**Error %**
1	230.802	5.0106	13.148	61.89
2	792.312	5.0106	10.95	54.24

As the acceleration measured by the accelerometer is proportional to differential capacitance measured. At those two frequencies 230.802 Hz and 792.312 Hz the device will show the wrong value with error as shown in table 1.

6. CONCLUSION

The modal analysis for single finger is done on ANSYS software and the mode shapes are found. The capacitance values for different values of frequencies are calculated. From above observation it is shows that, two modes are obtained at 230 Hz and 792 Hz. At these frequencies finger deform due to which device shows an error in acceleration value. From above range of frequencies the bandwidth of the device is found to be 562 Hz. In this range the accelerometer will give accurate value of acceleration

REFERENCES

[1]Zakriya Mohammeda,Ghada Dushaqa, Aveek Chatterjeeb, Mahmoud asrasa,"An optimization technique for performance improvement of gap-changeable MEMS accelerometers", Mechatronics 54, 2018, 203–216

[2] Yi Ma, Limei Xu, Hui Li, "Optimization Design of a Capacitive Micro accelerometer", 10, 2010,978-1-4244-5141

[3] Keya Sanyal, Kalyan Biswas, "Design Optimization of Capacitive MEMS Accelerometer for Improved Sensitivity", International Journal of Computer Applications, 2017 ,0975 – 8887

[4] Meftah Hrairi, Badrul Hanafi bin Baharom, "Design and Modeling of Silicon MEMS Accelerometer",11, 2011, 978-1-61284-437-4

[5] Mourad Benmessaoud ,Mekkakia Maaza Nasreddine, "Optimization of MEMS capacitive accelerometer", Microsyst Technol, 19, 2013,713–720

[6] Khairun Nisa Khamil, Kok Swee Leong, Norizan Bin Mohamad, Norhayati Soin, "Analysis of MEMS Accelerometer for Optimized Sensitivity", International Journal of Engineering and Technology (IJET), Vol 6 No 6, 2015

[7] Michal Szermer, Jacek Nazdrowicz,Wojciech Zabierowski, "FEM Analysis of a 3D Model of a Capacitive Surfacemicromachined Accelerometer", CADSM 2017

[8] Abdul Qader Ahsan Qureshi, Soheil Azimi,Albert Leung, Behraad Bahreyni, "Development of a micro-machined accelerometer for particle acceleration detection" ,Sensors and Actuators. A 280, 2018, 359–367

[9] Shudong Wanga, Xueyong Weia,Yulong Zhaoa, Zhuangde Jianga, Yajing Shen, "A MEMS resonant accelerometer for low-frequency vibration detection" ,Sensors and Actuators, A 283 ,2018, 151–158

[10] Samuel Jim�ez , Matthew O.T.Cole, Patrick S.K eogh , "Vibration sensing in smart machine rotors using internal MEMS accelerometers" , Journal of Soundand Vibration,377, 2016, 58–75