Chapter 19
Design and Simulation of Single-Axis MEMS Accelerometer for Low Acceleration Applications

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Abstract This work involves the design of a MEMS single-axis capacitive-type accelerometer for low acceleration applications. In this paper, the displacement amplification complaint mechanism (DaCM) is used to increase sensitivity of the device by amplifying displacement. The DaCM model was designed using graphical method, and ANSYS tool is used to compare the displacement results. The DaCM model with maximum displacement is integrated with capacitive-type accelerometer. This integration was done using Coventerware turbo tool. The results obtained were compared with the accelerometer without DaCM. The displacement values that were obtained with and without DaCM are 3.1e−1 and 4.2e−2 μm, respectively. The results prove that DaCM gives an improved sensitivity.

Keywords MEMS · DaCM · Capacitance

19.1 Introduction

Microelectro mechanical systems (MEMS) had been a fast-growing technology. MEMS devices can act both as sensors and actuators. Some of the widely used MEMS devices are microphone, gyroscope, accelerometers, etc. MEMS accelerometers are sensing devices used for the detection of acceleration. Capacitive-type accelerometers are the most commonly used. It consists of proof mass and interdigitated fingers for capacitive sensing. When acceleration is applied to the proof mass, it displaces. There will be a change in distance (d) or area (A) between any sensing fingers. When one of the parameter changes, the capacitance also changes. Capacitive-type

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accelerometers have advantages [1], like high sensitivity, good noise performance, low-temperature sensitivity and low power dissipation. All the fingers in capacitive type are connected parallel, and if the number of capacitors is increased, then this increases the sensitivity [2]. Capacitive-type accelerometers can be used for low g sensing ranging from 2 μg to several g's. Some of the examples for low g sensor applications are structural health monitoring, border infiltration, earthquake detection, etc.

For low g applications since the acceleration that is applied is very low, displacement is also low. In order to improve the device sensitivity, amplification is required. There are two types of amplification: mechanical amplification and electronic amplification. Researchers had found how mechanical amplification is preferred over electronic amplification [3]. Mechanical noise is less compared to electronic noise [3]. There are many types of mechanical amplification like force amplification and displacement amplification. Force amplification has been explained in [4] and with an amplification of 11. Further researchers have taken the idea of displacement amplification to design a displacement amplifier. Displacement amplification was done with compliant mechanisms. Compliant mechanisms are those that transmit motion, force or energy by elastic deflection of flexural members. Displacement amplification compliant mechanisms (DaCMs) are single-input-single-output-type mechanism where an input displacement is applied at the input point which generates an amplified output at output point.

19.2 Design Methodology

This section explains about modelling of basic MEMS accelerometer and the design of DaCM using graphical method as well as modelling of integration of basic accelerometer with DaCM.

19.2.1 Modelling of Basic MEMS Accelerometer

When an accelerometer is subjected to acceleration, there is some force that is induced and this makes the accelerometer to vibrate in certain direction depending on the spring and damper. Due to this vibration, there is some displacement of proof mass. The mechanical sensitivity is defined as the displacement of the proof mass per unit gravitational acceleration, and sensitivity is given by capacitance per unit gravitational acceleration. The model of a spring-mass-damper system is shown in Fig. 19.1. The basic equation of the spring-mass-damper system is given by

$$m\ddot{x} + b\dot{x} + kx = F = ma \tag{19.1}$$

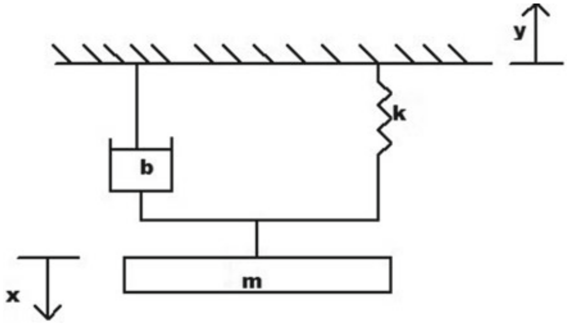

Fig. 19.1 Spring-mass-damper model of accelerometer

where m = proof mass, b = damping coefficient, k = spring stiffness, F = force, a = acceleration, x = displacement of proof mass.

19.3 Design of DaCM Using Graphical Method

Instantaneous centre method

Consider a rigid body in a plane having two points, and each point on the rigid body has different velocities. There will be point on the plane where there will be zero velocity, which makes the body to rotate about that point known as instantaneous centre of rotation. In order to compute this point, one has to draw a perpendicular line to the velocity and the point where both of them intersect; this is called instant centre point as shown in Fig. 19.2. The DaCM drawn using this method is shown in Fig. 19.3. By applying the instantaneous centre method, the DaCM was designed. The theoretical amplification of 16 was obtained. A solid model was drawn using solid edge and is shown in Fig. 19.4.

DaCM is a single member of flexure joints, whose required points are fixed. The designed model can be used for planar amplification that is for anyone of the single planar amplification. The input displacement and the output displacement are in the same direction. This DaCM design is integrated with a basic accelerometer for improving the sensitivity.

19.4 Modelling of Integrated Accelerometer with DaCM

The device is modelled using MEMS CAD tool called Coventerware turbo. The tool is used in 3D building of model and analysis of the accelerometer device. Here CoSolveEM which consists of mechanical domain and electrical domain analysis is used. All the electrodes and suspension ends are fixed, and acceleration of 1 g

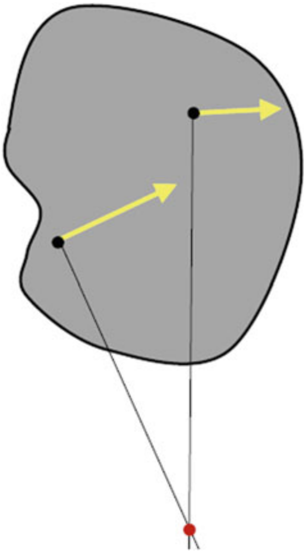

Fig. 19.2 Instantaneous centre method

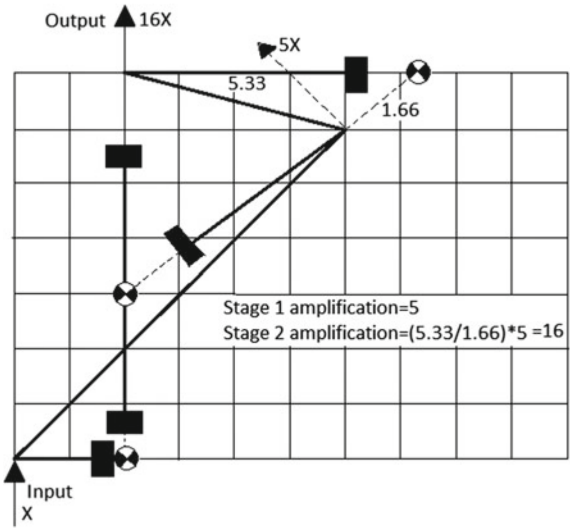

Fig. 19.3 Graphical design of DaCM

is applied in *y*-direction for the movable proof mass for mechanical domain. For electrical domain, 5 V is applied to the fixed electrodes and proof mass is connected to the ground.

Fig. 19.4 DaCM model using solid edge

The basic accelerometer model integration with DaCM is shown in Fig. 19.5. Here single crystalline silicon is used due to its properties like high melting point and low thermal expansion. The material has a density (*r*) of 2330 kg/m^3, Young's modulus (*E*) of 137 GPa, relative permittivity (*v*) of 11.7 and Poisson's ratio (*m*) of 0.278. Dimensions of the model are shown in Table 19.1. The meshed model of

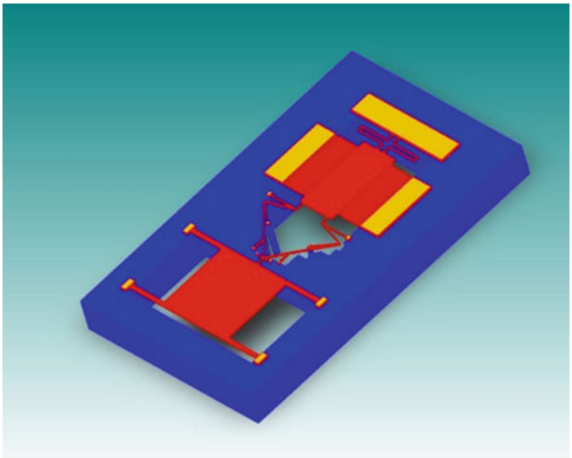

Fig. 19.5 Integrated accelerometer with DaCM

Table 19.1 Dimensions of integrated accelerometer model

Parameters	Length (μm)	Width (μm)	Thickness (μm)
Proof mass	1000	500	30
Fingers	10	300	30
DaCM spring suspension	50	500	30
DaCM proof mass	1000	1000	30
Folded beam suspension (one side)	1070	10	30

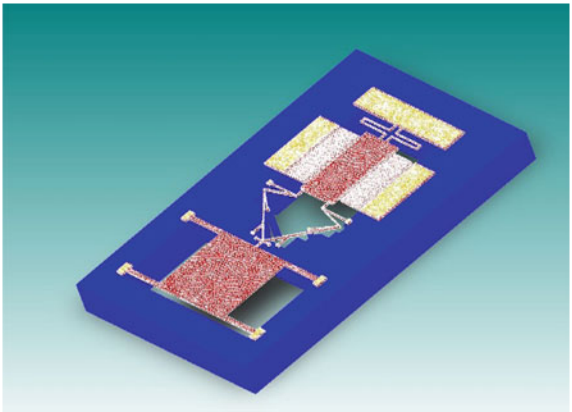

Fig. 19.6 Meshed integrated acceleration model

integrated accelerometer model is shown in Fig. 19.6.

19.5 Results and Discussion

ANSYS simulation of DaCM: The DaCM model that was designed graphically using instantaneous centre method was simulated using ANSYS tool by applying required boundary condition and suitable mesh size. The results obtained as shown in Fig. 19.7. There is a difference between theoretical graphical method and ANSYS as shown in Table 19.2. This difference is because of elastic losses in DaCM, mesh approximations done in ANSYS and some constraint that these tool uses to solve partial differential equations.

Displacement can be calculated using the basic formula

$$kx = ma \Longrightarrow x = ma/k \tag{19.2}$$

where x = displacement, m = mass, a = acceleration, k = stiffness.

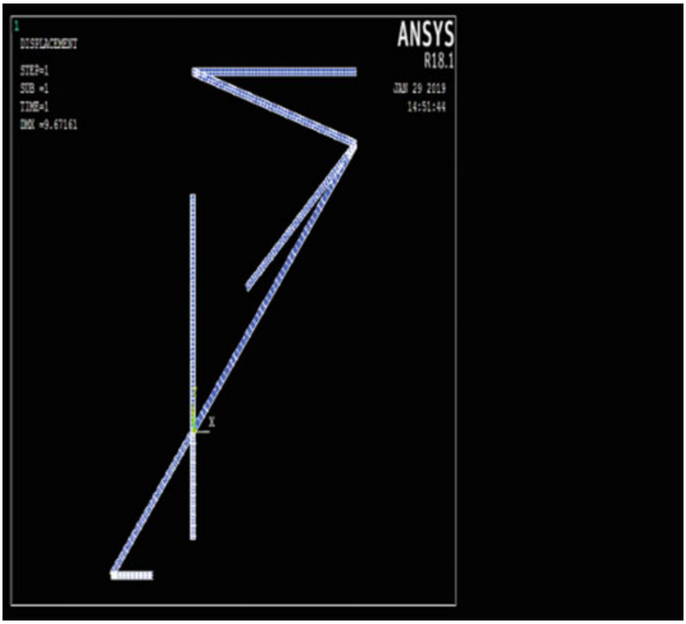

Fig. 19.7 ANSYS simulation

Table 19.2 Displacement amplifying factor comparison theoretical and ANSYS

	Theoretical	ANSYS
Displacement amplifying factor	16	9.5

Capacitance is given by

$$C = (\varepsilon A/d)N \quad \text{(general capacitance)} \tag{19.3}$$

where Ɛ = permittivity, A = area, d = distance between the plates, N = number of fingers on both the sides.

Figure 19.8 shows the when 1 g of acceleration is applied on an accelerometer without DaCM, a maximum displacement of 4.8×10^{-2} mm is observed. The displacement in y-direction is 4.170842×10^{-2} mm. The variation of capacitance, displacement and sensitivity with respect to applied acceleration is shown in Table 19.3.

When the applied acceleration increases, the displacement increases and the capacitance decreases. But the differential capacitance increases. The capacitance observed for 1 g acceleration is 1.895073 pF. Table 19.4 shows the results for input values. The simulation result of MEMS-based capacitive accelerometer integrated with DaCM is shown in this section. The analysis of displacement and capacitance is obtained in Coventerware. When 1 g acceleration is applied, a displacement of

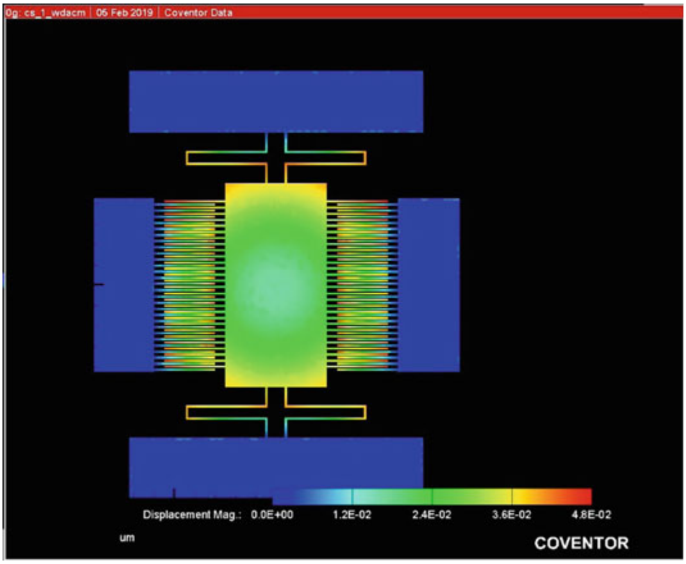

Fig. 19.8 Accelerometer without DaCM for 1 g

Table 19.3 Variation of displacement, capacitance and sensitivity with applied accelerations without DaCM

Acceleration (g)	Displacement (μm)	Capacitance (pF)	Sensitivity (pF/g)
0	0.03696418	1.884471	–
0.1	0.03743861	1.884468	18.84468
0.2	0.03791303	1.884465	9.422325
0.4	0.03886188	1.884460	4.711150
0.6	0.03981073	1.884455	3.140758
0.8	0.04075958	1.884449	2.355561
1	0.04170842	1.884444	1.884444

Table 19.4 Variation of displacement, capacitance and sensitivity with applied accelerations with DaCM

Acceleration (g)	Displacement (μm)	Capacitance (pF)	Sensitivity (pF/g)
0	0.08767009	1.895127	–
0.1	0.08767850	1.895121	18.95121
0.2	0.08768151	1.895116	9.47558
0.4	0.08769294	1.895105	4.7377625
0.6	0.08770437	1.895094	3.15849
0.8	0.08771580	1.859084	2.368855
1	0.08772723	1.895073	1.895073

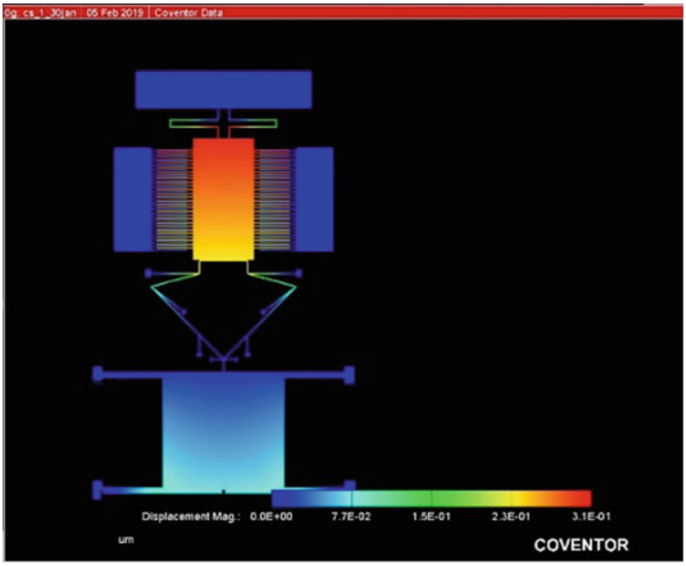

Fig. 19.9 Integrated accelerometer with DaCM for 1 g acceleration

8.772723×10^{-2} mm was observed in *y*-direction, and maximum displacement of 3.1×10^{-1} mm can be observed in Fig. 19.9.

On plotting for various accelerations, the values obtained for displacement vary linearly and this increases with g. The plot can be observed in Fig. 19.10. The plot is generated by acceleration versus capacitance.

One can observe from Fig. 19.11 that capacitance decreases with the increase in acceleration. On comparing the values from Tables 19.3 to 19.4, we can observe that displacement, capacitance and sensitivity are higher in case of accelerometer with DaCM (Table 19.5).

19.6 Conclusion

In this paper, single-axis MEMS accelerometer is designed, simulated and analysed for measuring low acceleration applications. The amplified displacement factor that is obtained theoretically and in ANSYS is 16 and 9.5, respectively. The results that were obtained from simulation of accelerometer with DaCM show that for 1 g acceleration; sensitivity of 1.895073 pF/g was achieved and without DaCM for 1 g acceleration; sensitivity of 1.88444 pF/g was achieved. The accelerometer model with DaCM gives higher displacement and sensitivity.

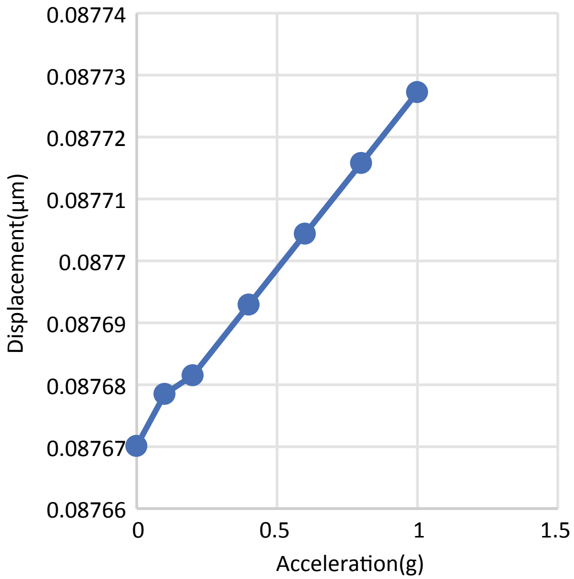

Fig. 19.10 Displacement versus acceleration

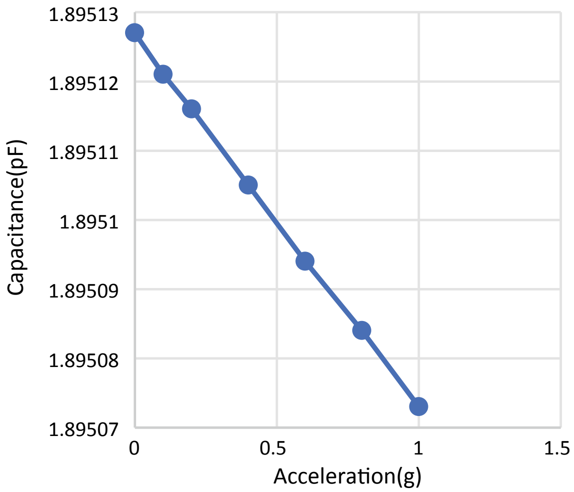

Fig. 19.11 Capacitance versus acceleration

Table 19.5 Comparison of displacement with DaCM and without DaCM

	Without DaCM	With DaCM
Maximum displacement for 1 g (mm)	4.8×10^{-2}	3.1×10^{-1}
Displacement in *y*-direction for 1 g (mm)	4.170842×10^{-2}	8.772723×10^{-2}

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