Research Article

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Design and optimization of differential capacitive micro accelerometer for vibration measurement

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Abstract: This paper deals with the design and optimization of a differential capacitive micro accelerometer for better displacement since other types of micro accelerometer lags in sensitivity and linearity. To overcome this problem, a capacitive area-changed technique is adopted to improve the sensitivity even in a wide acceleration range (0–100 g). The linearity is improved by designing a U-folded suspension. The movable mass of the accelerometer is designed with many fingers connected in parallel and suspended over the stationary electrodes. This arrangement gives the differential comb-type capacitive accelerometer. The area changed capacitive accelerometer is designed using Intellisuite 8.6 Software. Design parameters such as spring width and radius, length, and width of the proof mass are optimized using Minitab 17 software. Mechanical sensitivity of $0.3506 \mu\text{m/g}$ and Electrical sensitivity of $4.706 \mu\text{F/g}$ are achieved. The highest displacement of $7.899 \mu\text{m}$ is obtained with a cross-axis sensitivity of 0.47%.

Keywords: MEMS, capacitive accelerometer, U-folded suspension, Minitab 17 software, Intellisuite 8.6 software

1 Introduction

The technology from the last two decades introduced Micro Electro Mechanical Systems (MEMS) in many fields. MEMS accelerometers are used to sense 1-axis, 2-axis, or 3-axis acceleration. The acceleration is measured by an accelerometer using capacitive, piezoelectric, piezoresistive, optical, tunneling, and resonance transductions. Piezoelectric and piezoresistive accelerometer lags in sensitivity and linear-

ity [1]. A Capacitive type accelerometer is used instead of piezoelectric to improve the sensitivity. Capacitive micro-accelerometer has the advantage of low drift, low power consumption, low-temperature dependence, minimal cost and high sensitivity [2]. MEMS accelerometer becomes more popular and finds a place in automotive and precision applications [3]. A high dynamic range accelerometer ($g > 50$) finds its applications in the automotive sector (airbag deployment), biodynamic measurement, flutter testing, and high shock measurement. While a low-g accelerometer is used in large volume products like tablets, remote control system, smartphones, gaming system and toys [4]. A differential capacitive micro accelerometer is used to measure the hand-arm vibration in different brick structures [5]. A bulk micromachined in-plane capacitive accelerometer fabricated with an improved process flow, by etching only one-fifth of the wafer thickness at the back of silicon while forming the bar-structure electrode [6]. It greatly lowers the footing effect during deep reactive ion etching (DRIE), and increases the proof mass by 54% compared to the traditional way, resulting in both improved device quality and a higher yield rate [7].

An Area-changed accelerometer uses a ribbed finger structure on the movable mass as a differential capacitor and it is suspended over stationary electrodes. The differential capacitance is varied by varying the overlapping area of the proof mass and the fixed electrodes. High sensitivity can be obtained either by increasing the proof mass or lowering the spring constant of the suspension beam. Mechanical sensitivity of an area-changed capacitive accelerometer can be enhanced by optimizing the device geometry. Maximum displacement can be achieved by selecting the proper design structure of the area changed capacitive accelerometer. Simulation of the accelerometer can be done using MEMS CAD tools such as Intellisuite 8.6, Coventorware 2001, and Ansys software [8, 9].

2 Mass-spring-damper system

An accelerometer is dynamically modeled as shown in Figure 1 a simple spring-mass damper system. The accelerom-

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eter is excited along the sense direction with acceleration 'a', the proof mass 'm', suspended by a beam or spring is displaced under the effect of the inertial force in a direction opposite to the applied acceleration.

To apply the same model for differential capacitor area changed type, it needs some modification to withstand a high dynamic range and also possess better sensitivity and linearity. To improve the dynamic range, four suspension springs are introduced with two dashpots. Hence the total force will get divided equally into all four springs.

Figure 1: Dynamic model of basic accelerometer

Where:

M – Proof mass (kg),

B₁-B₂ – Dashpot,

K₁-K₂-K₃-K₄ – Spring constant (N/m)

Figure 2: Dynamic model of the proposed design

Figure 3: Free body diagram

To obtain the force equation of the proposed system, Newton's law of motion is used. The free-body diagram of the proposed accelerometer model and the free body diagram are shown in Figures 2 and 3.

Total force (Fa) acting on the system is given by Newton's second law of motion, which states that force developed by a body is directly proportional to the product of the mass of the body and its acceleration.

$$F_a = ma \quad (1)$$

$$F_a = F_m + F_{K1} + F_{K2} + F_{K3} + F_{K4} + F_{B1} + F_{B2} \quad (2)$$

Where:

F_a – applied force,

F_m – inertial force of proof mass,

$F_{K1}, F_{K2}, F_{K3}, F_{K4}$ – spring force,

F_{B1}, F_{B2} – Damping force.

From Eq. (2)

$$F_a = M \frac{d^2x}{dt^2} + K_1x + K_2x + K_3x + K_4x + B_1 \frac{dx}{dt} + B_2 \frac{dx}{dt} \quad (3)$$

Taking Laplace Transformation in Eq. (3),

$$F_a = MS^2X(S) + K_1X(S) + K_2X(S) + K_3X(S) + K_4X(S) + B_1SX(S) + B_2SX(S) \quad (4)$$

$$F_a = (MS^2 + K_1 + K_2 + K_3 + K_4 + B_1S + B_2S)X(S)$$

$$X(S)/F_a = 1/(MS^2 + K_1 + K_2 + K_3 + K_4 + B_1S + B_2S)X(S)$$

The above derived Eq. (4) states the final mathematical modelling of the proposed accelerometer design for high-g application. With the required specification for high-g system, the dimension and mass of the each components of the system can be calculated.

Proof mass, m

$$m = \rho_{si}(W_p L_p T_p + N W_F L_F t) \quad (5)$$

Where ρ_{si} is the density of silicon, w_p – width of the proof mass, L_p and T_p are length and thickness of proof mass, N is the number of sensing movable fingers, W_F, L_F, t are width, length and thickness of sensing fingers respectively.

Spring constant, K_x

$$K_x = \frac{NE(2L_1 + \pi R_1)W_1^2 T_1}{2(2L_1^4 + 4\pi R_1 L_1^2 + 24R_1^2 L_1^2 + 6\pi R_1^2 L_1 + 3\pi^2 R_1^4 - 24R_1^4)} \quad (6)$$

(N/M)

Where, E = young's modulus, L_1 & L_2 length of the folded beam, R_1 and W_1 are the radii of U-curvature of spring

and width of spring, T_1 is the thickness of spring, N is the number of folded U-spring.

Natural frequency, f_x

$$f_x = \frac{wX}{2\pi} = \frac{\sqrt{\frac{K_x}{m}}}{2\pi} \quad (7)$$

The bottom electrode and variable top electrode of the area changed micro accelerometer structure appeared to be a differential capacitance arrangement. Capacitance is measured while varying the area of an accelerometer which is given in Eqs (3)–(13).

Capacitance,

$$C = \epsilon_0 \epsilon_r \frac{A}{d} \quad (8)$$

$$C = \epsilon_0 \epsilon_r \frac{WL}{d} \quad (9)$$

When the area of the accelerometer is changed then the capacitance equation is rewritten as

$$C = N \frac{\epsilon L_F (W_F - W_d)}{2d} \quad (10)$$

Where:

N = Number of proof mass fingers

W_F = width of proof mass fingers

W_d = gap between the fixed electrodes

d = distance between fixed and movable electrode

The capacitance is amplified when the area of the capacitor is moved in a forward direction and capacitance is decreasing when the area of the capacitor is moved in quash direction.

Mechanical sensitivity of the area changed Capacitive accelerometer is expressed as

$$S_c = \frac{2\epsilon_0 N_f h (L_f - \Delta L_f) S_d}{d_0^2} \quad (11)$$

Where ΔL_f is the length not covered of the mobile finger, and if it is considered that much ΔL_f lower ($\Delta L_f \sim 0$). Mechanical sensitivity of the accelerometer is finally derived as

$$S = \frac{2\epsilon N L_F}{D} \quad (12)$$

where:

ϵ = Permittivity of air

N = Number of fingers

L_F = Length of the fingers (μm)

D = Distance between the top electrode (μm)

Cross axis sensitivity is measured as

$$\begin{aligned} \text{Cross axis sensitivity} = \\ \text{Displacement at Y axis/Displacement at X axis} \end{aligned} \quad (13)$$

3 Design using Intellisuite 8.6

3.1 Mask layer design

Micro Accelerometers are designed and fabricated using various modules available in Intellisuite 8.6 software. IntelliMask is a mask layer editor from Intellisuite 8.6 software, it provides the environment to create, edit and modify mask design's for MEMS devices. From the mathematical modeling results, the design parameters for differential capacitive area changed micro accelerometer has been obtained and tabulated in Table 1.

Table 1: Dimensions for parameter design

S.NO	Parameters	Dimension
1	Proof mass	Length
		300 μm
		Width
2	Suspension spring	285 μm
		Thickness
		40 μm
3	Material	Length
		285 μm
		Width
4		60 μm
		Thickness
		40 μm
5		Silicon
		<110>

The suspension beams are placed outside the plane of the micro accelerometer (proof mass). Three mask layers were modeled and developed in IntelliMask and shown in Figure 4.

Figure 4: Mask layout for design parameter

In Figure 4 U-shaped spring has been placed instead of the folded beam to improve linearity. In the design layer, 0 lengths and width of the U-spring have been chosen as $285\ \mu\text{m} \times 60\ \mu\text{m}$. Another design layer 2 for trenches formation in proof mass with the same length and width has been varied to $285\ \mu\text{m} \times 32.5\ \mu\text{m}$. Finally, the layer 3 fixed electrode differential capacitor plate is designed with length and breadth as $275\ \mu\text{m} \times 22.5\ \mu\text{m}$. All this layer will have their effect in improving the displacement of proof mass furthermore when the micro accelerometer operating at its full range [10].

Anchors are placed in-plane with the proof mass and suspension springs are placed between these anchors. This design has been expected to provide high linearity and very low cross-axis sensitivity. All the above-created models are used for the fabrication process.

3.2 Fabrication of micro accelerometer

The fabrication process flow sequence can be viewed using the inbuilt animation module FabViewer in IntelliFab. This sequence can also be saved in an image sequence, which is shown in Figure 5. Initially, a Silicon substrate with an orientation of 110 is taken as a base material. The mask

layer is created with a U-shaped spring. The deep reactive Ion Etching is done after the mask layer is created. Similarly, a fixed mask layer 1 is created. Then differential capacitance arrangement is fabricated after etching. Finally, the top and bottom view of the fabricated accelerometer is shown. The proof mass is deposited over the fixed electrode through the sacrificial insulating layer. Capacitance is measured between the top and bottom electrodes after removing the sacrificial layer.

4 Design analysis

The fabrication files are then exported to the Thermo Electro Mechanical analysis (TEM) module of Intellisuite 8.6. This allows carrying out static, dynamic and frequency analysis over the fabricated designs. A load of 100 g is applied on the x-axis, 1g on the y-axis and 1g on the z-axis and the mesh analysis is done. The displacement for the given load and the displacement of the cross axis is shown in Figure 6.

The above-obtained displacement at the X axis is not appropriate for general application. So the design is further processed for optimization to produce better displacement (Eq. 3).

5 Electrode design

Electrodes are used to measure the acceleration data during sudden mechanical excitation or vibration. Capacitive type accelerometers are widely used in most applications, because of their high sensitivity and low-temperature coefficient of expansion. Among different capacitance sensing techniques, the differential capacitance technique acquires more attention among researchers due to its improved performance than the normal capacitance method.

The basic capacitance formula for measuring acceleration data is,

$$C = \epsilon_o \epsilon_r \left(\frac{A}{d} \right) \quad (14)$$

Where:

C – capacitance between plates

ϵ_r – relative permittivity

ϵ_o – permittivity of air

A – Area of electrode plates

d – Distance between electrode plates

Figure 7 shows the difference between the regular capacitance and differential capacitance sensing techniques. For differential capacitance, the general formula is written

Figure 5: Fabrication process flow sequence for design

Figure 6: Displacement at axis x, y, z

Figure 7: Differences between ordinary capacitance and differential capacitance

to be,

$$C = \epsilon_o \epsilon_r \left\{ \frac{l([b + \Delta x] - [b - \Delta x])}{d} \right\} \quad (15)$$

Where:

C – capacitance between plates

ϵ_r – relative permittivity

ϵ_o – permittivity of air

l – Length of overlapping area of electrode

b – Breadth of overlapping area of electrode

Δx – change in overlapping length of electrode

d – Distance between electrode plates

6 Optimization of micro-accelerometer

6.1 Optimisation techniques

Three main types of problems can be handled by the optimization techniques are single variable functions, multi-variable functions with no constraints, multivariable functions with both equality and inequality constraints. In problems with equality constraints, the Lagrange multiplier method can be used whereas the Kuhn-Tucker conditions can be used to identify the optimum solution for the problems with inequality constraints. In this present work, Taguchi Method is used where the design of experiments is carried out for the optimization process (Eq. 15).

Various designs are modeled using Intellisuite 8.6 is shown in Figure 8 and the resultant displacement at the x, the y axis is measured and cross-axis sensitivity is calculated by using Eq. (12). In Table 2 correlating all the designs, Design 5 shows maximum displacement at X-axis and least cross-axis sensitivity when compared to all designs. Hence the optimized design (design No. 5) is further modified and performance is analyzed.

The spring width was maintained constant as 5 μm for the first three designs and the mass length, mass width and spring arc radius are varied. For the first, second and third design the mass length is 300, 1400 and 2500 μm , the

Figure 8: Various design modeled

Table 2: Design parameter and their result

Design No.	Spring width (μm)	Mass length (μm)	Mass width (μm)	Spring arc radius (μm)	Displacement (μm)		Cross axis sensitivity (%)
					X	Y	
1	5	300	285	25	0.0013152	0.000194	14.75281326
2	5	1400	1242.5	37.5	0.0987405	0.0066004	6.684551932
3	5	2500	2200	75	0.306031	0.10393	33.96061183
4	12.5	300	1242.5	75	0.143323	0.0062926	4.39053048
5	12.5	1400	2200	25	7.89953	0.0455015	0.576002623
6	12.5	2500	285	37.5	0.0023013	0.0004069	17.68035145
7	20	300	2200	37.5	0.694688	0.0052972	0.762527926
8	20	1400	285	75	0.0009006	0.0002855	31.70273722
9	20	2500	1242.5	25	0.0024304	0.000181	7.448536643

mass width are 285, 1242.5 and 2200 μm and the spring arc radius are 25, 37.5 and 75 μm respectively. Next, the spring width was maintained constant as 12.5 μm for design 4, 5 & 6 and 20 μm for design 7, 8 & 9, and the mass length, mass width and spring arc radius are maintained as maintained in design 1, 2 & 3 in the order of design 3, 2 & 1. From all these designs, comparatively, design 5 shows the least cross-axis sensitivity (%).

7 Static analysis

Based on analysis results, the performance of the designed micro accelerometer was tested with the system require-

ments. The displacement data for applied input acceleration was shown in Figure 9.

From Figure 9, the displacement for 100 g of acceleration applied on micro accelerometer was measured to be 9.848 μm at X-axis whereas the displacement of the accelerometer which does not contain holes on its proof mass is recorded as 7.899 μm . It is due to the holes in proof mass that increase the displacement of the accelerometer. Also, it helps in improving the sensitivity of the device. The hole on the proof mass will not cause any damping issues. The mass of the optimized design is 3.619×10^{-7} kg, and the spring constant, k is 6.2642 N/m.

The occurrence of cross-axis sensitivity for the acceleration originated out of the sensing axis has to be analyzed. This will avoid the further occurrence of an error in the out-

Figure 9: Optimised design displacement at 100 g

Table 3: Optimised design result

Acceleration (g)	Displacement (μm)		Cross axis sensitivity (%)
	X	Y	
10	0.984828	0.00570218	0.579002628
20	1.96965	0.0102272	0.519239459
30	2.95447	0.0147522	0.499317983
40	3.93929	0.019272	0.489225216
50	4.92411	0.0238022	0.483380753
60	5.90893	0.0283272	0.479396439
70	6.89376	0.0328523	0.476551258
80	7.87858	0.0373773	0.47441671
90	8.8634	0.0419023	0.472756504
100	9.84822	0.0464273	0.471428339

Table 4: Output parameters of designed micro accelerometer

Parameters	Achieved
Operating range	0-100 g
Natural frequency (Hz)	662.15
Cross axis sensitivity (%)	0.47
Mechanical sensitivity ($\mu\text{m/g}$)	0.3506
Electrical sensitivity ($\mu\text{F/g}$)	4.706
Material used	Silicon <110>
Sensing technique	The area changed differential capacitor technique

Figure 10: Cross axis sensitivity vs. acceleration **Figure 11:** Displacement vs. acceleration

put signal. Table 3 shows the displacement and cross-axis sensitivity for applied acceleration (10-100 g).

Graph 10 shows the response from initial acceleration to a range up to 100 g where the cross-axis sensitivity lowers gradually. From the literature survey, it is well known that cross-axis sensitivity should be within 2% of actual sensing sensitivity. For better performance, it is much necessary to limit it to 2%. The above results show that the designed micro accelerometer exhibits cross-axis sensitivity in the

range of 0.47% to 0.57%. So the micro accelerometer will provide better performance.

The displacements for applied acceleration are shown in Figure 11. Displacement of proof mass varies the overlapping area of the proof mass over the differential capacitive plates. The length of the overlapping area varies concerning constant width. This will cause an increment in capacitance in one capacitor plate and a decrease in capacitance in another plate.

The overall performance shows that the designed micro accelerometer withstands a dynamic range up to 100 g with a natural frequency of 662.15 Hz. By using the optimized values of spring width, spring arc radius, proof mass length, and proof mass width, the highest displacement of 9.848 $\mu\text{m/g}$ is achieved. It provides a mechanical sensitivity of 0.3506 $\mu\text{m/g}$ and electrical sensitivity of 4.706 $\mu\text{F/g}$. Table 4 shows the system achieved results which are calculated by using the above formula.

Hence the designed micro accelerometer satisfies all the requirements and it performs well, even at its full dynamic range.

8 Conclusions

In the present work, an area changed differential capacitive micro accelerometer has been mathematically designed and analyzed.

- From the mathematical results, design simulation was done using Intellisuite 8.6 software package.
- To improve the sensitivity of the micro accelerometer at high shock range area changed capacitive technique has been used. Instead of using folded suspension beam, a U-shaped suspension beam was used. This will improve the linearity of the micro accelerometer. And also holes are made in the proof mass to improve the output.
- The performance analysis was done using the Thermo Electro Mechanical analysis module (TEM) from Intellisuite 8.6 software.
- The result shows that the designed micro accelerometer will work better. It can replace the existing piezoelectric and piezoresistive micro accelerometer, which lacks high sensitivity and linearity at high temperatures.

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