



MEMS CAPACITIVE ACCELEROMETER – DESIGN & SIMULATION

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Abstract: The study in this paper involves Finite Element Analysis (FEA) of a MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS) based 3D accelerometer. The configuration of accelerometer has been made and analyzed using COMSOL Multiphysics. The design presented in this paper consists of a square shaped proof-mass with four serpentine springs supporting it. The design is simulated using solid mechanics module and electrostatics module. The design can be used for advanced low-G MEMS applications, biomedical applications, defense applications such as aerodynamic control, inertial measurement, inertial guidance, airborne sensor/communication devices, bio fluidic chips or “BioFlips”.

Keywords: MEMS, accelerometer, COMSOL Multiphysics, finite element analysis.

I. Introduction

Micromachining technologies have enabled a many fold increase in the functionality of the mechanical sensors and, at the same time have enabled a reduction in their size thus achieving unprecedented levels in miniaturization. New markets for MEMS (Micro Electro Mechanical Systems) Accelerometers have emerged owing to their enormous capabilities with respect to performance, miniaturization, reliability, low price, and low power consumption. For all MEMS devices, for achieving sufficient low cost, a high production volume must be achieved. The most important markets that provide high volume opportunities are consumer products, automotive, computers and peripherals, and medical and biological applications [1]. These include navigation, air bag control, motion sensing, roll over, GPS with E-compass for automotive market, camera stabilization, 3D gaming, motion dialing, text scroll, hard disk protection, free fall detection, image stability, motion detection in consumer applications, and motor stability, seismometers in industrial applications [2]. Other application fields like avionics, naval, space and the gas & petroleum industry require specific sensors with dedicated performance enhanced features like increased robustness, enhanced shock and vibration tolerance, capability to work under harsh environmental conditions and are thus manufactured by specialized companies and are provided at an elevated cost [1]. The various defense applications include intelligent bombs, satellites like “picosat”, smart ammunition, MEMS F/SA device for submarine torpedo counter weapon, booster rockets for ejection seats in F-14 fighter jets, “Bioflips” for smart assessment of warfighter’s medical condition, etc. [3].

II. 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 Figure 1 shows the final mechanical 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. This design has the capability of multi-axis sensing, out of plane detection: rotation and has high shock survivability. Figure 2 shows the basic working idea of the MEMS capacitive accelerometer.

III. Accelerometer Design Considerations

Resolution, bias-instability, cross-axis sensitivity, nonlinearity and voltage sensitivity are the main considerations for evaluation of a MEMS accelerometer [5]. In order to consider an accelerometer ‘high performance’, it has to be evaluated in all above stated areas.

Resolution is the most important criteria and is defined as the minimum resolvable acceleration by the device. For inertial navigation applications, bias-instability is an important property and is defined as change in accelerometer output to variable change. The sensitivity of accelerometer to off-axis accelerations is known as cross-axis sensitivity. The change in the output voltage due to 1g acceleration input is called voltage sensitivity. And,

nonlinearity is defined as the deviation of the output of the device from the linear input-output curve plotted in accordance with the sensitivity of accelerometer [5].

Figure 1. The final design of MEMS Capacitive Accelerometer.

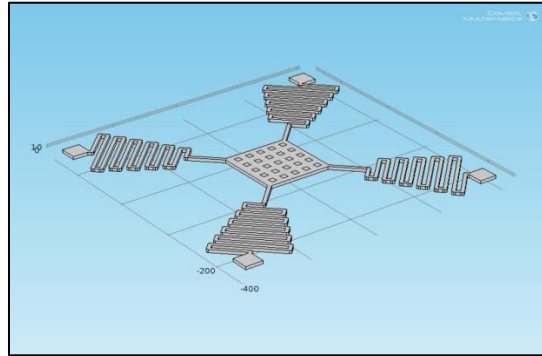
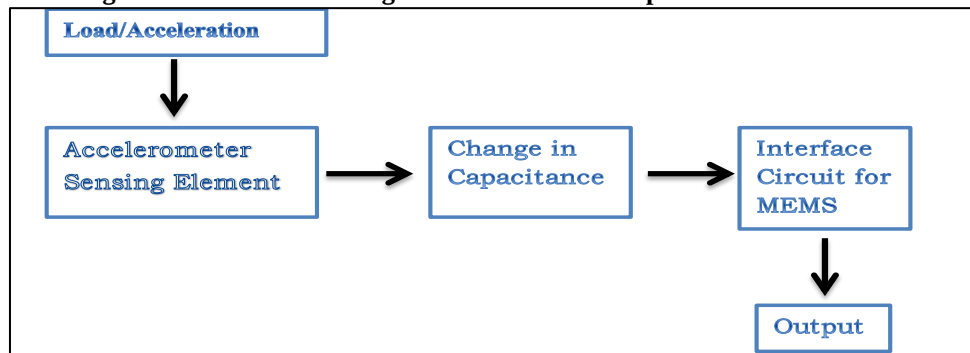


Figure 2. The basic working idea of the MEMS Capacitive Accelerometer.



In order to design a high performance accelerometer, three basic procedural steps are to be considered. First and most important being the selection of the process technology because it directly affects the structure and performance of the device. Second being the designing of the read-out circuit and third is choosing the packaging facilities [6].

The bandwidth of operation and noise floor determine the resolution of an accelerometer. The two different noise sources in accelerometers, the first being mechanical noise which is due to Brownian noise and is expressed in terms of total damping and mass size and the second one being the electronic noise which is due to the read-out circuit of the device [4]. Vacuum packaging can be used to reduce the damping of accelerometer and to achieve high quality factor. But reduced damping has the drawback of reduced bandwidth and high quality factor has the disadvantage of increased vibrations in the static seismic mass at resonance frequency. Therefore, in order to prevent oscillation at frequency of resonance, accelerometers with high quality factor and static seismic mass should be operated with forced balanced operation.

An accelerometer's voltage sensitivity is related to the sense capacitance, resonance frequency, and the readout circuitry. Here, sense capacitance and resonance frequency are design considerations that depend on the process. Resonance frequency can be reduced by lowering the spring constant or by increasing the seismic mass size. Small sense capacitance, on the other hand, can be a big problem for sensing the displacement because the output of the accelerometer is degraded by parasitic capacitances. There are two ways to solve this problem. First is that the accelerometer can have a high sense capacitance so as to reduce the effect of the parasitic capacitances. Second is to monolithically integrate the accelerometer with readout circuitry in order to decrease parasitic capacitances [6]. However, the main design consideration for an accelerometer is SNR i.e. Signal to Noise ratio and unfortunately, it is effected by high sense capacitance as high values of sense capacitance need greater overlap area and smaller gap area which can only be achieved by high aspect ratio process technology, but, achieving a high aspect ratio microstructure is not possible with surface micromachining [7].

Another parameter to be considered is nonlinearity which is geometry dependent in nature. Nonlinearity can be introduced in the output of the accelerator due to varying gap sense capacitances [7]. For such capacitances, differential sensing scheme is for linearity is necessary. Nonlinearity is a result of mismatch that is introduced by the formation of differential sense capacitances during process variations. Thus, the process has a great effect on the accelerometer's linearity. In order to eliminate the mismatch in between sense capacitances, force feedback operation is used [8].

The sensitivity of the accelerometer to aging and changing conditions is depicted by Bias Instability. For example, if the structural material of accelerometer is temperature sensitive, than, a change in the ambient temperature of the room/place of operation, will change the resonance frequency of accelerometer. Sensitivity of accelerometer is also affected by the change as well as the sense capacitance due to change in temperature. This results in loss of repeatability in the accelerometer output. This problem can be solved by isolating the accelerometer from changing environmental conditions by using good quality packaging [9]. Another reason for low bias instability is aging. This factor particularly affects the resonant accelerometers because of their proof-mass keeps vibrating continuously. In order to keep this factor in check, process technology selection plays an important role [10]. Another important design consideration is read-out circuitry. If the force balance operation is used with the read-out circuitry, some of the design flaws can be easily eliminated [11]. And finally, for a reliable, stable and efficient operation of accelerometer, packaging must be done effectively.

IV. Capacitive Accelerometer Design

As discussed in the previous section, resolution of accelerometer is of utmost value. On order to enhance the value of resolution, sense capacitance value must be increased and the natural resonant frequency must be decreased. However, both these design considerations are dependent upon the fabrication process [12]. Further, in order to achieve maximum resolution, the spring constant of accelerometer should be low. And, minimum achievable spring constant depends on the size of springs and size of the seismic mass. Minimum width of the springs is defined by the resolution of the lithographic process.

The parameters described in Table 1 shows material properties of the structure. Silicon is used for the seismic mass and poly-silicon for the anchors. In order to optimize the design for fabrication purposes, various versions of the design are made. These versions differ by varying thickness, spring length and width.

In order to simulate the design, the simulation software COMSOL Multiphysics is used. The module used is MEMS module which works in conjunction with structural mechanics and electrostatics module. COMSOL Multiphysics is a finite element simulator and has an additional advantage that the governing differential equations for the device dynamics can be easily changed.

Simulation in COMSOL Multiphysics is a five stage procedure. In the first stage, the design is created. In the second stage, physics is applied which includes applying material to the design as well as applying boundary conditions to it. The third stage is to mesh the design. Meshing is important, as meshing allows the study of the whole design and not just some specific points. The fourth stage is processing where the design is simulated and results are acquired. And the final stage is post-processing where the acquired results are studies and plotted.

Table 1: Dimensional and material properties of the accelerometer.

Notation	Value	Determination	Unit
l_p	200	Length of proof mass	μm
b_p	200	Breadth of proof mass	μm
h_p	10	Thickness of proof mas	μm
σ_y	7×10^9	Yield strength of Silicon	N/m^2
E	169	Young's Modulus of Silicon	GPa-s
ν	0.28	Poisson's ratio	
α	2.5×10^{-6}	Thermal expansion coefficient	$\text{mt/mt}^\circ\text{C}$
P	2.3	Density	g/m^3
d_0	3	Initial capacitance gap	μm
K	24.5	Spring Constant	N/m

V. Simulation Result

The following figure displays the obtained result after the simulation of the MEMS based capacitive accelerometer in COMSOL Multiphysics.

Figure 3. Total Displacement.

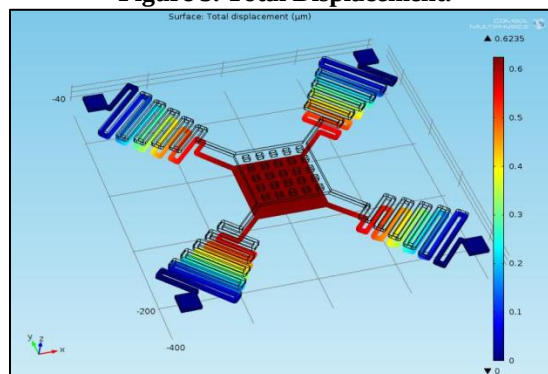
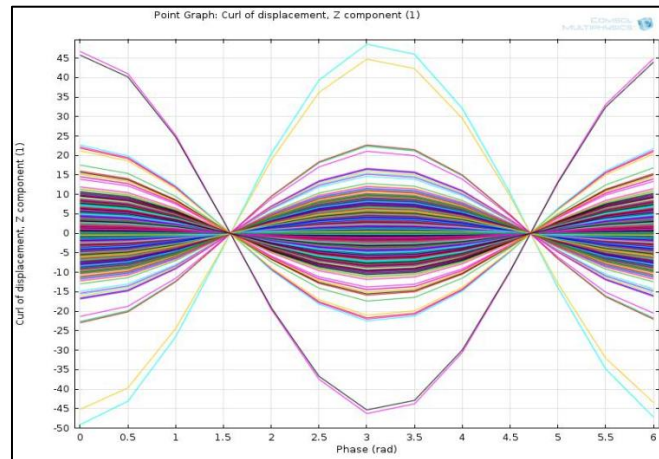


Figure 4. Curl of Displacement.



VI. Results and Conclusions

The following are the conclusions that summarize the parameters that govern the function and performance of the accelerometer.

1. The acceleration range is 0 to 7g. The proposed accelerometer is for low-g applications.
2. Owing to the study of frequency response the following conclusion is made that the bandwidth should be more than 100 Hz.
3. The voltage sensitivity is 0.34 V/ μm .
4. The capacitive sensitivity is 0.112 fF/g.
5. The sensitivity is 0.13 $\mu\text{m/g}$.
6. The cross axis sensitivity is $2.3167 \times 10^{-6} \mu\text{m/g}$.

The theoretical and simulated analysis differs by an error of 7% only and therefore, can be neglected.

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