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Modeling and Design of MEMS Accelerometer to detect vibrations on chest wall

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Abstract* —A slight vibration is felt when a hand is placed on the chest. The vibration has great information as sounds, functions of heart and lung motion. The screening of heart disease can be carried out by listening to heart sounds. Recent developments in miniature, high sensitive MEMS accelerometers enable the recording of heart sounds using a chest worn sensor which can be used for ambulatory measurement of cardiac activity. In this project, the modeling and design of the MEMS accelerometer is carried out with respect to the vibrating frequency of the chest wall and the range of acceleration is ± 4g can be measured with increased sensitivity and decreased cross-sensitivity. The design utilize the capacitive effect for the acceleration sensing. The modeling is done using COMSOL MultiPhysics Software.

***Keywords*—MEMS accelerometer, heart sounds, capacitive effect.**

I. INTRODUCTION

Miniaturization of biomedical sensors has increased the importance of microsystem technology in medical applications, particularly microelectronics and micromachining[1]. Electrocardiograph (ECG), Phonocardiograph (PCG), Ultrasound cardiography (UCG) are costly devices and are difficult for long-time and ambulatory monitoring of heart functions and its motion. As a new idea which was being worked on recently by various researchers, it was found that, the slight vibration of the chest surface due to heartbeat allows visualizing the heart motion for assisting and to understand heart function[4]. The method is based on a MEMS vibration sensor called MEMS accelerometer (Inertial sensor) and some signal/image processing units. Vibration mode of the chest has three or four frequency bands, which allow visualizing region of the heart. Contour of heart wall with data of 1-50 Hz frequency and locations of valves with higher frequency can be made visible. The technique may allow to monitoring heart motion in an operation or after an operation, understanding irregular heartbeat, heart motion during sleeping and in state of mental tension without using an UCG or ECG devices.

In this work, the modeling and design of this MEMS accelerometer is done i.e., the steps before the fabrication part of it. Acceleration measurement is achieved by a proof-mass, spring, and damper system made up of microfabricated structures. A lumped-parameter of the system is developed using COMSOL MultiPhysics software.

II. BACKGROUND

Microelectromechanical systems (MEMS) is a technology involving small systems with both mechanical devices and electrical components. MEMS devices include accelerometers and gyroscopes in navigation and safety systems, digital micromirror devices (DMD) in projectors, DNA microarrays for rapid DNA analysis, and inkjet print heads in many printers. Recent demand for MEMS devices has made it one of the fastest growing technologies. MEMS technology provides the benefits of small size, low weight, high performance, easy mass-production and low cost [3].

Many types of micromachined accelerometers have been developed and reported in the literature. The vast majority of these devices have in common a mechanical sensing element consisting of a proof mass attached by a mechanical suspension

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system to a reference frame. The accelerometer can thus be modeled by a second order mass-damper-spring system as shown in Fig 1.

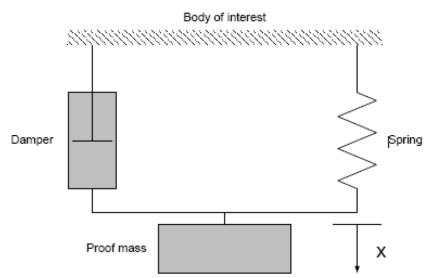

Fig1. Lumped parameter model of an accelerometer consisting of proof-mass, spring and a damping element

Any external inertial forces due to acceleration displace the support frame relative to the proof mass according to Newton's second law. This in turn applies a force of **F=ma** on the spring with **m** being the mass of the proof mass and **a** being the acceleration. The spring is deflected until its elastic force equals the force produced by the acceleration. In the first order, the force acting on the spring is proportional to its displacement **x**, **F=kx**, with **k** being the mechanical spring constant[3]. Therefore, in a static situation the displacement is proportional to the acceleration:

$$x = \frac{m}{k}a$$

Where 'x' is the displacement
'm' is the mass
'k' is the stiffness constant
'a' is the acceleration

The second order mechanical transfer function can be described as:

$$\frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}}$$

where b is the damping coefficient, s is the Laplace operator and a(s) is the acceleration. The natural resonant frequency (rad/s),of this system is given by :

$$\omega_n = \sqrt{\frac{k}{m}}$$

Comb-drive accelerometer usually consists of two finger structures, called fixed finger and movable finger. The fixed fingers are fixed to the accelerometer frame. The movable fingers are attached to a proof-mass and suspended by flexible elements to the frame. The device senses any external acceleration which is transferred to the proof-mass through the flexible elements such as springs. The proof-mass and movable fingers move along the direction of body force, the fixed comb remains stationary. This movement changes the capacitance between the fixed finger and the movable finger. The capacitance is measured using electronic circuitry.

III. PROPOSED DESIGN

The structure of the MEMS sensor can then be designed as a mechanical mass-spring system where the mass is one side of a parallel plate capacitor and the frame of the accelerometer is the other. The device then has a nominal capacitance and will change as the proof-mass responds to acceleration events. These changes can be monitored along each axis and then analyzed to provide information on the motion occurring[2]. The design features a proof-mass with interdigitated fingers along each side that correspond to opposing interdigitated fingers extending from the frame. This is called comb- drive accelerometer design. T/he capacitor plates are arranged such that there are two types of plates :fixed and movable capacitor plates shown in Fig 2. The movable capacitor plates are attached to the proof-mass and so when the proof-mass moves with the input vibration (acceleration), the movable capacitor plates moves towards and backwards (or to the left / right) of the fixed plates. This structure then creates many small parallel plate capacitors that will sense motions in-plane with the x- and y- axes[2]. The capacitors, or fins, extend from a proof mass suspended by a crab leg flexure spring structure shown in Fig 2.

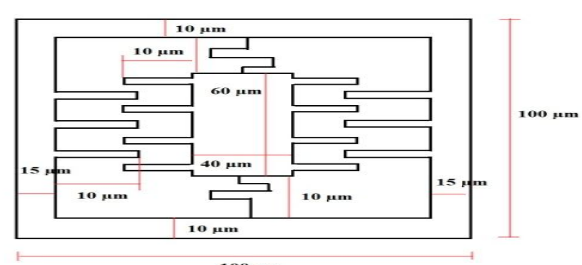

Fig 2. MEMS Accelerometer Structure with springs in vertical direction

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IV. DESIGN OF PRELIMINARY PARAMETERS

The parameters of the transfer function are proof- mass 'm', spring constant or stiffness constant 'k' and damping co-efficient 'B' can be obtained as follows: Let,

- Width of the spring is 'W'
- Length of the spring is 'L'
- Thickness of the spring is 'H'
- Area Moment of inertia is 'I'
- 'μ' is the viscosity of air @ 20°C, μ =18.75x10^{-6} N-s/m^2

S.No.	Parameter	Formula used	Value (with units)
1	Young's modulus of Silicon	-	190,000 MPa
2	Proof-mass, m	-	3x10^{-6} kg
3	Frequency of Heart vibrations, f	-	40 Hz
4	Natural frequency, ω	$f=\frac{\omega}{2\pi}$	251.2 rad/s
5	Spring constant, k	$\omega=\sqrt{\frac{2k}{m}}$	0.0946 N/m
6	Area moment of inertia, I	$k=\frac{48EI}{L^3}$	2.24x10^{-24} m^4
7	Width of the spring, W	$I=\frac{TW^3}{12}$	2.99x10^{-6}m
8	Damping co-efficient, B	$B=\frac{2\mu LW}{H}$	0.7875x10^{-8}N-s/m
9	Damping Ratio,ε	$\frac{B}{2\sqrt{km}}$	0.734

I. Design Parameters

Thus, the transfer function obtained using the above parameter values is :

$$\frac{X(s)}{F(s)}=\frac{k}{\frac{m}{k}s^2+\frac{B}{k}s+1}$$

$$\frac{X(s)}{F(s)}=\frac{0.0946}{3.17\times10^{-5}s^2+8.324s+1}$$

The transfer function obtained is simulated in MATLAB using the Simulink tool with a step input of 4μm as amplitude to obtain a resulting displacement of 2 μm (Fig 3.).

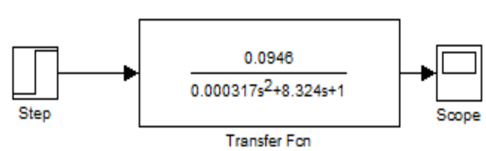

Fig 3. Transfer function with step input

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The output from the transfer function is given to scope with input values i.e., acceleration (±g) in X- axis and output displacement (µm) in Y- axis is shown in Fig 4.The result was obtained such that for a step input of 4, the output displacement is linearly increasing from 2.36 µm to 2.52 µm. This is shown in Fig 7.2. The values of proof mass ‘m’, spring constant ‘k’ and damping co-efficient ‘B’ which gives this transfer function is taken. If these values of m, k and B are adjusted, a more linear output is obtained.

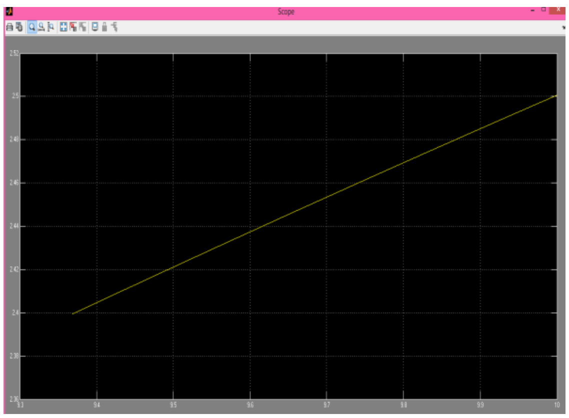

Fig 4. Output in scope – Acceleration Vs Displacement

V. MODELING IN COMSOL MULTIPHYSICS

The accelerometer was modeled in 3D using COMSOL Multiphysics. The simulation and analysis are also carried out in this software. These simulations are necessary to find the maximum amount of accelerating force the MEMS accelerometer will be able to withstand and to find the variation in the comb-drive capacitance with respect to the displacement.

A. *Model definition*

The simulations where done using the Electrostatics and Solid mechanics physics in the MEMS module. These physics were selected using the ‘Add Physics’ option in the software.

B. *Geometry*

The model is set to 3-axis geometry and then the physics is added. The next step is setting the global definitions like parameters or variables or functions etc. Here the parameters like size are set for the substrate, proof-mass, frame, comb fingers : width W, height H, depth D (in µm) which are shown in the following Fig 5.

Parameters

Parameters

Name	Expression	Value
subW	100	100.00
subH	100	100.00
subD	5	5.0000
pmW	50	50.000
pmH	60	60.000
pmD	4	4.0000
frm1W	10	10.000
frm1H	60	60.000
frm1D	5	5.0000
frm2W	30	30.000
frm2H	10	10.000
frm2D	5	5.0000
cmbW	10	10.000
cmbH	2	2.0000
cmbD	4	4.0000

Fig 5. substrate, proof-mass, frame, comb fingers : width W, height H, depth D (in µm)

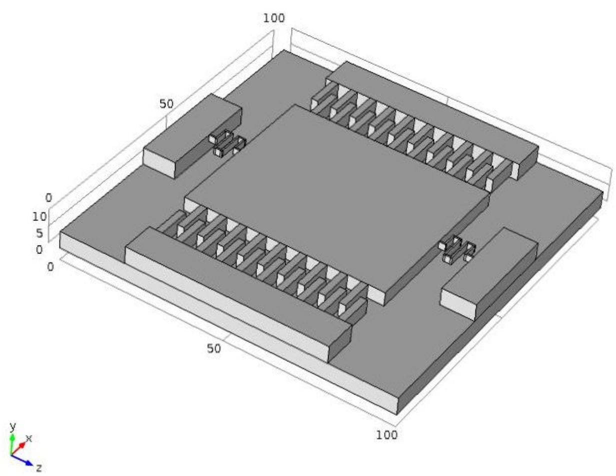

Fig 6. 3D structure of the accelerometer

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Many blocks are added to the geometry according to the sizes of the substrate, proof-mass, comb fingers to form the following MEMS accelerometer structure shown in the Fig 6.

C. Equations for the domains

The Capacitance is calculated using the equation:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{g_{ap}}$$

Electrical field (E) and electric displacement

(D) vectors can be defined according to the

expressions:

$$E = -\nabla V$$

$$D = \varepsilon_0 \varepsilon_r E$$

The Capacitance can also be calculated using the

following relation which is the energy relation :

$$W = \frac{1}{2} C V_S^2$$

The capacitance can be easily measured when the electrostatic energy is known.

D. Boundary conditions

The boundary conditions are given to the fixed electrodes attached to the frame on two sides and movable electrodes that are being attached to the proof-mass. A potential of 1V is applied to the movable electrodes attached to the proof-mass and to simulate a 1 V potential gradient across the electrodes, the fixed electrodes are kept at the ground.

E. Meshing

The Fig 7. shows the meshed structure of the MEMS accelerometer. The Mesh feature in comsol (meaning : interlocking) enable the discretization of the geometry model into small units of simple shapes, referred to as mesh elements. There are different types of mesh elements such as : tetrahedral, triangular, quad etc. Here, tetrahedral is chosen as the type of mesh element.

VI.CONCLUSION

The proposed work of modeling and design of MEMS accelerometer is carried out with literature survey to find the suitable sensing technique. The sensing technique used is the capacitance method. The capacitors are used in the comb-drive form and hence the accelerometer is called as capacitive comb-drive MEMS accelerometer. The mathematical modeling step is done to find the parameter values such as mass, spring constant, damping co- efficient,

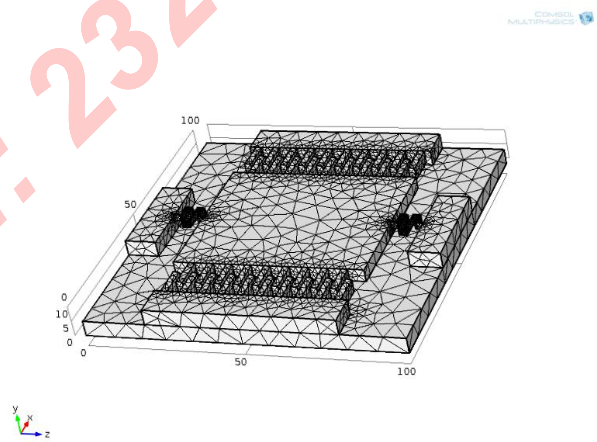

Fig 7. Meshed structure of the accelerometer

damping ratio and finally the transfer function with input acceleration and output displacement is obtained. The capacitance modeling yielded the equation for total change in capacitance when the movable plates moves to the right and left when the proof- mass is subjected to an input acceleration. The transfer function obtained in the mechanical modeling was given in MATLAB using the specific tool, Simulink with a step input. The output was visualized in scope. The MEMS accelerometer is modeled using Comsol Multiphysics software in 3-axis and simulated to get the corresponding displacement for the input acceleration.

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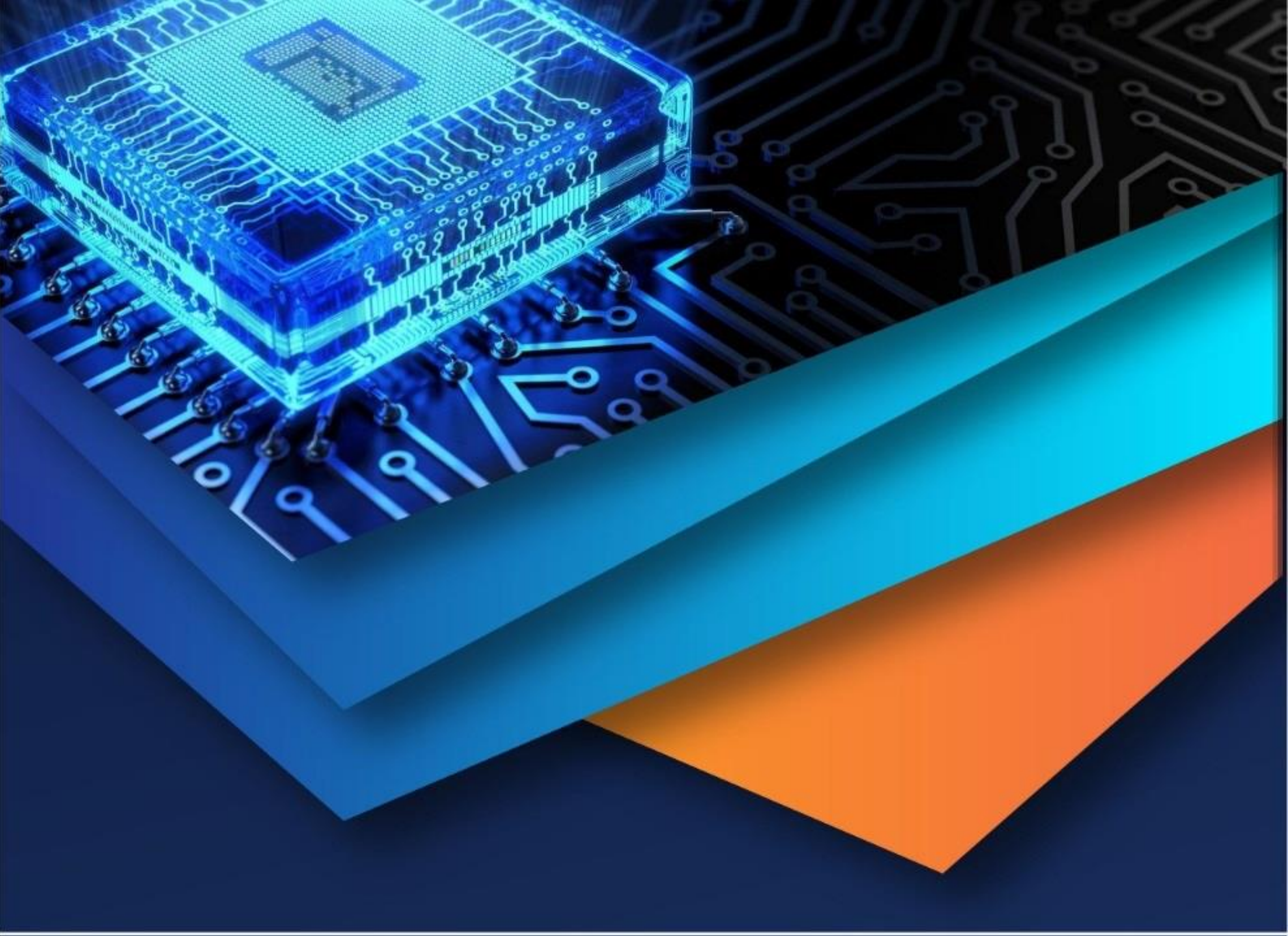

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