Analysis of MEMS Accelerometer for Optimized Sensitivity

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Abstract— Sensitivity is an important element of a sensing process, and it is part of the open-loop gain of the sensor. This makes it a strong inverse relationship between sensitivity and bandwidth for any class of sensors. The geometrical of the accelerometer, mass width, beam (length and width) of the device and its sensitivity are analyzed theoretically and also using finite element analysis software, COMSOL Multiphysics®. Hence, the optimization analysis concluded that desired sensitivity can be achieved by adding number of fingers and adjusting the length of the beam. Preliminary results show that the sensitivity of the device increases by significantly by 38%.

Keyword- MEMS, capacitive, accelerometer, sensitivity

I. INTRODUCTION

This These days, numerous research studies are made on MEMS based micro-accelerometer that focus on optimizing the device sensitivity [1]. With a smaller size compared to the conventional design of the accelerometer, it weighs lesser, functions more efficiently which then contributed to cheaper manufacturing cost. MEMS accelerometers can be found used in most of our everyday life items which ranging from telecommunication to health and safety like airbag deployment systems used in vehicles. By detecting the negative acceleration of the automobile, accelerometers are the sensor to use. These sudden changes of the negative acceleration are depending on the changes to the types of the sensor that will be used.

This comb finger type capacitive accelerometer proved in numerous of the research studies to be most successful type accelerometer since it gives high sensitivity in capacitance due to its large sensing area [1][2]. However, the researches on comb finger type accelerometer are limited. By tracing back to the application of comb finger type device, this design has been used in actuator for a long time [2]. The study successes in comb finger as used in actuator can be used as the reference for comb finger type as being used in accelerometer. Regardless of what type being used in accelerometer or actuators, resonant frequency and the variation of the structure in comb finger type are the interested parameters that are being considered in the structural analysis and to optimize the sensitivity[1][2].

The current work tries to fill the absence in the recent study [1][2][4] and the aim is to develop a methodology comprising the analytical and numerical study for structural analysis and optimization of the sensitivity for comb finger type accelerometer. In this project, the finding will be referred closely to simulated result of Sharma,K and Benmessaoud & Nasreddine since both published model are also optimized the device displacement sensitivity. The displacement sensitivity is an important element of the sensing process, and it is part of the open-loop gain of the sensor. So, it is a strong inverse relationship between sensitivity and bandwidth for any class of sensors (The relationship between mass widths, beam (length and width) of the device are analyzed to achieve a higher sensitivity [3].

This objective of this study is to optimize the MEMS accelerometer structure by enhancing the device sensitivity. It is design and simulated using COMSOL Multiphysics.

II. DESIGN ANALYSIS

A. *Principles of Operation*

Interface in capacitance sensor have some great features where it can function equally as an actuator and a sensor. It is highly sensitive but naturally unaffected to current temperature [5]. To understand the operation of accelerometer is by simply using the principle of a mass spring system which is the second order mass-spring-damper system [6].

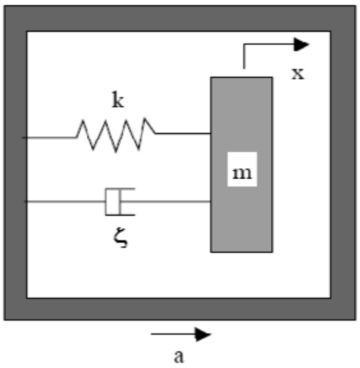

Fig. 1. Mass-Spring-Damper System [7]

$$M_s.\frac{d^2x}{dt^2}+D.\ \frac{dx}{dt}+K_s.x=M_s.a_{ext} \tag{1}$$

where the given the spring constant, K_s, the damping coefficient as D, the movable mass as M_s and the external acceleration as a_{ext}.

If the equation (1) changes to transfer function of second order using the Laplace transform:

$$\frac{X(s)}{A(s)}=\frac{1}{s^2+s.\frac{D}{M_s}+\frac{K_s}{M_s}}=\frac{1}{s^2+s.\frac{\omega_r}{Q}+\omega_r{}^2} \tag{2}$$

Given the resonant frequency as ωr and the quality factor as Q.

Accelerometers are often designed based on mechanical movement or vibration. In this research, four folded beams or springs are chosen because they can lower the effects of spinning and to sustain a great sensitivity [8].

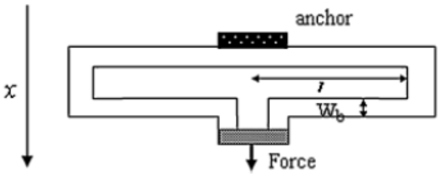

Fig. 2. Suspension beam structure features [9]

The beam structure in Δx direction of the spring constant can be seen in Fig. 2.

B. *Capacitive sensing technique*

As mentioned earlier, capacitive sensor is commonly used type of sensor which can also turn into an actuator. It can be a high accuracy sensor with a minor temperature coefficient [10]. It can straight away detect a variation of parameters like chemical composition, humidity, motion, proximity, electric field and other signals [11]. From the signal received, an electrical signal will be resulting from a point, or properties of the dielectric material [12]. Sensors are made from conductive detecting anodes/cathodes (electrodes) in a dielectric, where detection circuits with proper amount of excitation voltages; they can change a capacitance difference into a voltage.

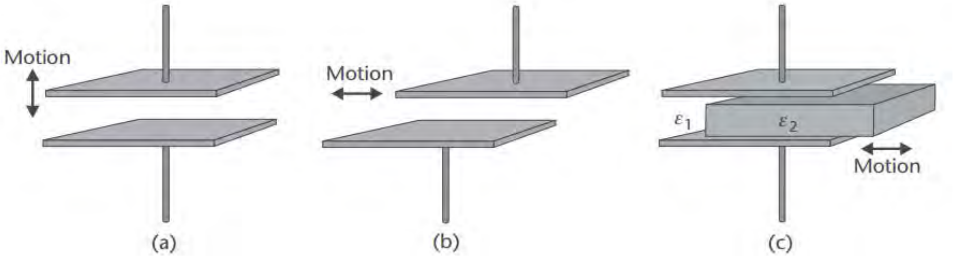

Fig. 3. Basic capacitance model of displacement sensors: (a) movable plate, (b) variable area, and (c) movable dielectric [13]

By referring to the basic configuration above, the electrodes are placed in two parallel plates. One of them is movable and the other one is fixed.

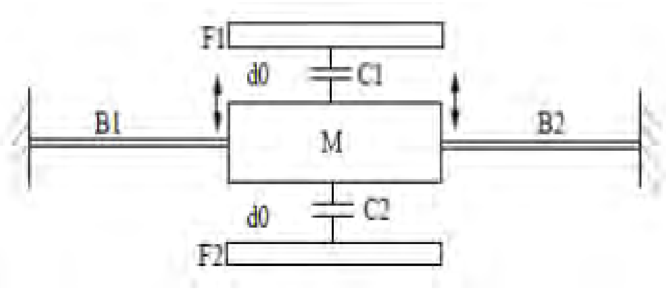

Fig. 4. Schematic Diagram of capacitive MEMS [14]

The figure above shows the parallel configuration that has both a fixed electrode space and area of intersection. When a dielectric material is applied to the structure motion with a given dissimilar permittivity that slot in between of both electrodes, this design will be easily effected by the temperature. Then the detecting parameters of distance, area and dielectric will experience some changes that affect the signal output [13]. The other parallel plate configuration, transverse comb structure can rise the value of capacitance even at a small size. By referring to a simple MEMS structure for differential capacitance in Fig. 4, it shows the moving mass denoted as *Ms*, the fixed fingers as *F1* and *F2* and the beam as *B1* and *B2* [14].

As the moving mass is attached through the bendable beams to a substrate, this creates differential capacitances of *C1* and *C2* with the upper and lower of the fixed finger. In the stationary mode, the moving mass *Ms* positioned in the middle of the fingers, thus:

$$C_1=C_2=\frac{\varepsilon_0.S}{d_0} \qquad (3)$$

where dielectric constant of free space is ε_0, the joint area between mass and the fingers stated as *S*, and the stationary gap of the capacitance as d_0. The bending of beams and displacement of a moving mass *Ms* happen from the acceleration in the upper direction. An electrostatic force, F_d, result from the moving mass when M experienced the voltage V0 given to the nominal voltage Vnominal and the fixed fingers of F1.

$$F_d=\left(\frac{\varepsilon_0.\ S.\ V_0^2}{2.d_0^2}\right) \qquad (4)$$

A certain threshold value cannot be exceeded by the supply voltage where the refraction is set not more than 1/3 of the gap of the capacitance, d_0. This applied to the vertical electrostatic or the moving mass will be held fixed at the fingers and ensue a short circuit.

C. Analysis of the Device

When force is applied to the accelerometer in the horizontal direction of the device with given acceleration, *a*, the inertial force will bend in the opposite direction of the given acceleration. As the proof mass is given with the appropriate force/acceleration in the selected direction, the fingers moved as well and given a displacement, hence the sensitivity of the device is defined by this. This condition can be referred to the principle of operation where an elaboration of the spring-mass model is presented. It is important to find each of the parameters before starting the FEM analysis.

When there is no acceleration given, ($a = 0$), the static capacitance of the comb accelerometer will be:

$$C_{10} = C_{20} = C_0 = \frac{\varepsilon.N_f.L_f.t}{d_0} \qquad (5)$$

where ε is the dielectric constant of free space. When acceleration given ($a \neq 0$) to the movable mass on the left direction laterally, it will have an inertial force in the opposed direction by *x*. A minor deflection is assumed, estimated by ($x << d_0$), where both sides of capacitances C_1, C_2 are changing as well and the changes on differential capacitance, ΔC is:

$$\Delta C= C_2-C_1= \frac{2.\varepsilon.N_f.L_f.t}{d_0}.\left(\frac{x}{d_0}\right)= 2.C_0.\left(\frac{x}{d_0}\right) \qquad (6)$$

The above equation gave the minor deflection value where the displacement *x* of the movable fingers is proportional to the changes of the differential capacitance change, *C*. If the beam is bent around (angle < 5), basic spring-mass model can be deliberated for the accelerometer.

The resonant frequency f_0 of the comb accelerometer can be calculated:

$$f_0= \frac{1}{2.\pi}.\sqrt{\frac{K_{total}}{M_s}} \qquad (7)$$

First, the total of movable mass, *Ms* for the accelerometer was required before finding parameter in the equation above:

$$M_s = \rho.t.(W_m.L_m + N_f.\ W_{f.}\ L_f) \tag{8}$$

where the density of polysilicon is ρ and the thickness of the device is *t*. Spring constant K_s of one section of the beam can be designed by:

$$K_s = \frac{12.E.I_b}{L_b^3} \tag{9}$$

where the inertial momentum is stated as I_b for the beam. Each of the folded beam also needs to be analyzed, thus the spring constant presented as K_{fold} [15]. But since all the folded beams are identical in size and connected in parallel, K_{total} can be presented by:

$$K_{total} = 4.K_{fold} = \frac{2.E.t.\ W_b^3}{L_b^3} \tag{10}$$

After the design parameters have been finalized and obtained, the parameters can be used to create a model device for the simulation part. Once the device is simulated and analyzed, the sensitivity can be found. For this device, sensitivity analyses are based on the displacement of the device. The displacement of the device is stated as:

$$x = \frac{F_{inertial}}{K_{total}} = -\frac{M_s.a}{K_{total}} = -\frac{\rho.a.(W_m.\ L_m + N_f.\ W_{f.}\ L_f)\ L_b^3}{2.E.\ W_b^3} \tag{11}$$

And, the displacement sensitivity of the device can be found [16] as :

$$S_d = \frac{M_s.g}{K_{total}} = \frac{\rho.(W_m.\ L_m + N_f.\ W_{f.}\ L_f)\ L_b^3}{2.E.\ W_b^3} \tag{12}$$

By referring to the analysis of the sensitivity on the above equations, preliminary conclusion can be made:

(a) In equation (12), the displacement sensitivity of S_d is inversely proportional to the beam width, W_b, which is $Sd \propto (1/W_b^3)$. This means the device sensitivity deviates quickly as the beam width decreases its values. This shows that the width of the beam is very sensitive with any adjustment made to it. As the beam width decreases, sensitivity increases. By modifying other parameters (such as increasing the number of fingers, altering the beam width or length), the high sensitivity device might be obtained as well. By using the increments from the published paper [1], the values used are from 2 µm to 3 µm, 4 µm, 5 µm and 6 µm.

(b) From the same equation (12), it also shows that S_d is also directly proportional to the beam length which is $S_d \propto L_b^3$ where this change increases the sensitivity and usage of an area of the device. But the sensitivity obtained from the changes of the beam length is not increasing rapidly like changing the width of the beam length. As for the length of beam, the increments follow the values from the published [1], which are from 290 µm to 300 µm, 310 µm, 330 µm and 360 µm.

(c) By changing (increases the value) the width and length of the proof mass, sensitivity of the device, S_d increases as well as it is directly proportional to each other, $S_d \propto L_m, W_m$. To see the changes, values of the increments follow the values from the published paper [1], which are from 70 µm to 65µm, 80 µm, 90 µm and 100 µm.

(d) By referring to equation (12), the sensitivity, S_d will slowly increase when the number of fingers of the comb accelerometer, Nf increases. Using this method, it will consume the area of the device but as long as the increases are within the outermost device areas which are 460µm×630µm, it is still acceptable. Furthermore, by incrementing the beam length, L_b, the sensitivity of the device will improve significantly.

All values in point a), b) c) and d) will be used to determine this theoretical analysis in order to support the simulation work.

III. METHODOLOGY

A. Selection of Model Structure

By using this published model [1], the model structure, model physic in the simulation and its boundary condition, material properties and some of the dimensions are determined. Published model is used in this research project to verify the MEMS model built with COMSOL Multiphysics®.

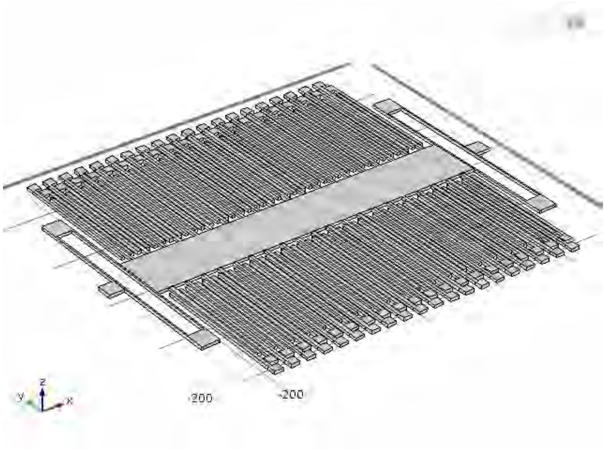

Fig. 5. Designs of MEMS comb accelerometer

B. *Design Parameters*

The design parameters and material properties needed to construct and model the structure were taken from the published model [1]:-

TABLE I. Material Properties

Material Properties	***Label***	**Values**
Density	$\boldsymbol{\rho}$	$2.33\times10^3\ kg / m^3$
Young’s Modulus of polysilicon	E	$1.70\times10^{11}Pa$
Dielectric permittivity polysilicon	ε_r	*11.9*
Electric constant	ε_o	$8.854x10^{12}(F/m)$
Poisson’s ratio	v	*0.22*

TABLE II. Structure Label and Dimension

Input Design Parameters	**Label**	**Dimension**
Beam Width	W_b	2 µm
Beam Length	L_b	290 µm
Proof Mass Width	W_m	70 µm
Proof Mass Length	L_m	434 µm
Device Thickness	t	4 µm
Total of Sensing Finger	N_{sf}	40
Fingers Width	W_f	4 µm
Fingers Length	L_f	160 µm
Capacitance gap between left/right of movable fingers	d_0	2 µm

IV. RESULTS

The structure is built based on the simulation condition of device characteristics in the Table I and II. The simulations were performed using the application mode of Electrostatics (to determine the capacitance) and Solid Mechanics (to determine the displacements) in the MEMS module. The simulation results for Fig. 6 and 7 are presented based on the section Design Analysis, part C: Analysis of the device.

In Fig.6, The huge difference can be seen where 73% of decrease in the data when the beam is increased from 2 µm to 3 µm. As the beam width decreases, sensitivity increases.

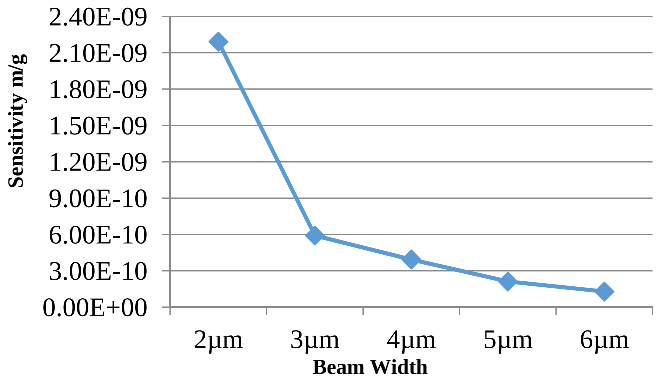

Fig. 6. The displacement sensitivity versus beam width, W_b

But this can only work theoretically, because in micromachining the device, if the width is less than 2µm, the device will be too delicate and easily spoilt. This result support the previous analysis made by Sharma, K [1].

For Fig. 7, result showed, as the parameters of the width of the proof mass increases, the sensitivity increases as well. All of the results prove that the simulation analysis matches the previous analytical analysis expectation in Equation (12) where S_d are directly proportional to the beam width which is $S_d \propto W_m$. With these changes, it increases the sensitivity and area of the device.

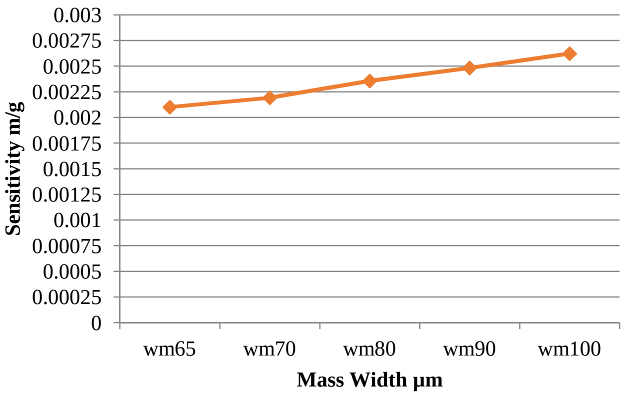

Fig. 7. Sensitivity versus Mass Width, W_m for each of number of fingers

Another method to optimize the sensitivity is by increases the numbers of fingers with the increments of beam length. The results shown below in Fig.8, the optimized model increase by 27% to 38% for both analytical and simulated when the number of fingers increases from 32 to 40. This shows that the model sensitivity has improved appropriately according to equation (12).

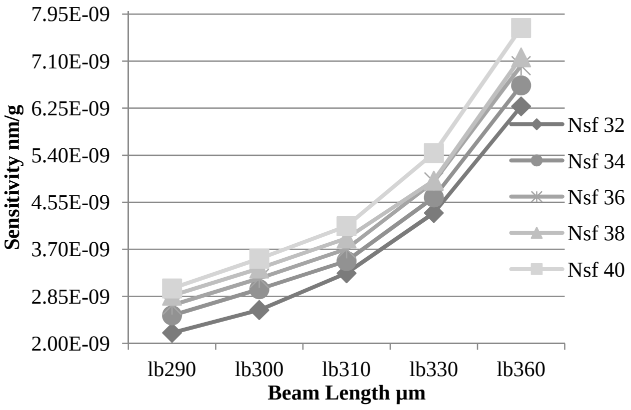

Fig. 8. Sensitivity versus Beam Length, L_b for each of number of fingers

TABLE III. Percentage of increase between Analytical and Simulated result for both Optimized and Original models

	Simulated (m/g)	**%**
Optimized	3.5301E-09	
Original	2.1921E-09	37.90
	Analytical (m/g)	**%**
Optimized	3.1754E-09	
Original	2.30467E-09	27.42

V. CONCLUSION

As a conclusion, by increasing the number of fingers and the beam length dimensions, the sensitivity of the device improves vastly. Based on this analysis, an optimized MEMS accelerometer is designed. Simulation results showed that the device has a sensitivity of 3.5301 nm/g. The proposed accelerometer device can be implemented for ±50g automobile airbag applications.

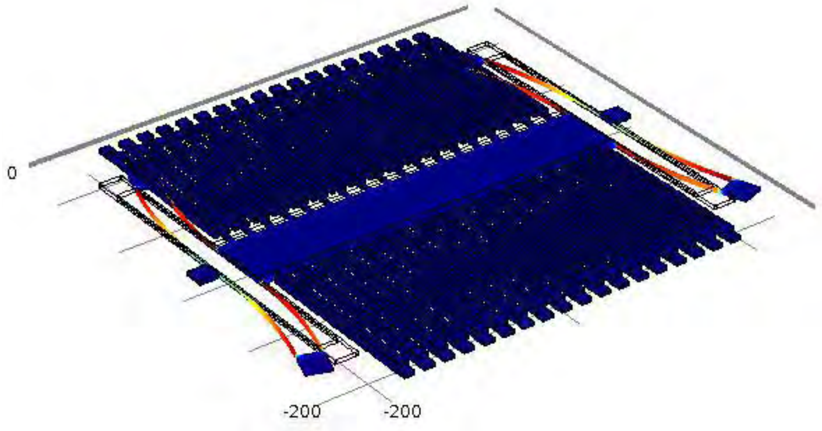

Fig. 9. Simulated Results of Optimized MEMS Accelerometer

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REFERENCES

[1] Sharma K, Macwan IG, Zhang L, Hmurcik L, Xiong X, Design Optimization of MEMS Comb Accelerometer, 2008.

[2] W.C.Wong. Analysis Of The Suspension Beam In Accelerometer For Stiffness Constant And Resonant Frequency By Using Analytical And Numerical Investigation. Universiti Sains Malaysia, 2007

[3] Bernstein, Jonathan, An Overview of MEMS Inertial Sensing Technology. Sensormag , 2003, February 1.

[4] Benmessaoud, Mourad, & Nasreddine, Mekkakia Maaza. Optimization of MEMS capacitive accelerometer. Vol 19, 713-720, 2013

[5] Stilson, Tim, Accelerometer (ADXL50). Human Computer Interface Design, Stanford University, 1996.

[6] Vijayakumar S, Vijila G, Alagappan M, Anju Gupta, Design and Analysis of 3D Capacitive Accelerometer for Automotive Applications. Paper presented at the COMSOL Conference Bangalore, Bangalore, India, 2011.

[7] K.H Denishev, M.R Petrova, ACCELEROMETER DESIGN. Electronics, 2007.

[8] Gabrielson, T. B, Mechanical-thermal noise in micromachined acoustic and vibration sensors. IEEE Trans. on Electron. Dev, Vol 40, 903-909, 1993.

[9] LC, Kuan, Wireless MEMS accelerometer for real-time., Case Western Reserve University, 2008.

[10] Boser, Bernhard E, Capacitive Sensor Interfaces, 1996.

[11] Baxter, L.K, Capacitive sensors-design and applications R. J. Herrick, 1997.

[12] Fischer-Cripps, A. C, Newnes interfacing companion: Computers, Transducers, Instrumentation and Signal Processing, 2002.

[13] Beeby, Stephen, Graham Ensell, Micheal Kraft, Neil White, MEMS Mechanical Sensor. London: Artech House Inc, 2002.

[14] Xiong, Xingguo, Built-in Self-test and Self-repair for Capacitive MEMS Devices. University of Cincinnati, Ohio, 2005.

[15] Gupta V, Mukherjee T, Layout synthesis of CMOS MEMS accelerometers., Carnegie Mellon University, Pittsburgh, 2012.

[16] Bais B, Majlis BY, Low-g Area-changed MEMS accelerometer using bulk silicon technique. Am J Appl Sci 5(6)(1546-9239), 626-632 , 2008.