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Analysis and Design of Micro-Electromechanical Sensors

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Abstract— In developing Micro Electro Mechanical Systems (MEMS), using the MATLAB software , many modeling tasks in MEMS can be implemented easily. Additionally, their performance can also be determined so that it satisfies the needs of various fields. With this kind of approach, the performance of the devices can be easily expanded, as well as reducing the time and cost of MEMS production. This paper focuses on the modeling of silicon MEMS accelerometer in an attempt to design a surface micro-machined accelerometer that satisfies certain pre-determined specifications.

Keywords-component; Acceleration, Accelerometer, Design, Displacement, MEMS, Modeling, Velocity

I. INTRODUCTION

Nowadays, there is a huge interest in Micro Electro Mechanical Systems (MEMS) technology. This industry has been established in recent years and has generated a rapid introduction of new products in various applications such as automotive, biochemical analysis, communication, etc. MEMS promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making possible the realization of complete systems-on-a-chip. It is an enabling technology allowing the development of smart products, augmenting the computational ability of microelectronics with the perception and control capabilities of micro sensors and micro actuators and expanding the space of possible designs and applications [1]. Hence, it is important to continuously develop MEMS technology so that it will give a lot of benefits especially in the automotive industry.

Modern simulation tools are also becoming more frequently used for MEMS devices. Instead of constructing the MEMS devices in the laboratory, the simulation of MEMS using programs like MATLAB, ANSYS, etc. has many advantages in terms of time, and cost. The simulation of the device can be repeated continuously until the desired result is achieved. Moreover, it can be used in almost every engineering discipline. Once the process is completely done, the data is used to build the device in laboratory.

Micro-accelerometers or accelerometers are one of the most important types of MEMS device, which have the second largest sales volume after pressure sensors [2]. The large volume demand for MEMS accelerometers are due to their capability to be used in many applications especially automotive industry. They can be used to measure tilt, motion, position, vibration, and shock.

Generally, an accelerometer consists of either a proof mass, seismic mass, or comb finger suspended by compliant beams anchored to a fixed frame. The operation can be modeled by a second-order mass-damper-spring system. External acceleration can be measured by relative displacement (capacitance) or by suspension-beam stress (piezoresistive).

This paper focuses on the modeling of a silicon MEMS accelerometer in an attempt to design a surface micro-machined accelerometer that satisfies certain pre-determined specifications.

II. DESCRIPTION OF THE ACCELEROMETER

In the case of a MEMS accelerometer, significantly different arrangements are made because of the very limited space available in micro-devices. A silicon beam with an attached mass constitutes a spring mass system. The air in the surrounding space is used to produce the damping effect. The structure that supports the mass acts as a spring. Most MEMS accelerometers are built on the principles of mechanical vibration.

The accelerometer consists of a silicon mass that is suspended by a spring. Acceleration will cause a force to act on the mass, which is consequently deflected by a distance x (Fig. 1). The measurement of acceleration relies on Newton's classical law. Hence, the equation of motion for the mass, m, is given by

$$m\ddot{\chi} + \beta\dot{\chi} + k\chi = ma \qquad \text{(a)}$$

where β and k are the damping coefficient and the spring constant, respectively. Thus, the acceleration, a, can be determined by measuring the net stretch or compression of the spring.

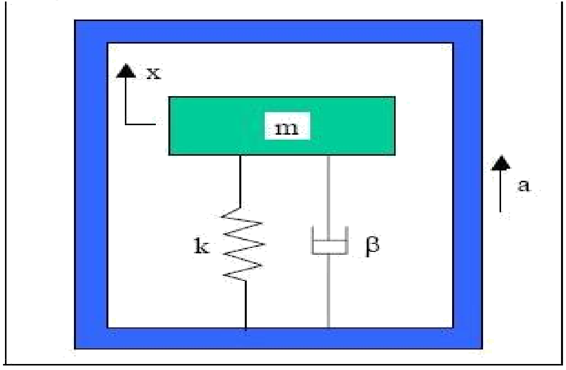

Figure 1. Accelerometer sensing principle.

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The MEMS accelerometer has a configuration as shown in Fig. 2. The silicon mass is suspended by eight beams which are also fabricated from silicon. A piezoresistor is implanted on the beam to measure the deformation of the attached mass, from which the amplitudes, and thus the acceleration, of the vibrating mass can be correlated [3]. By using micromachining technology, the silicon mass is shaped like a truncated pyramid (Fig. 3).

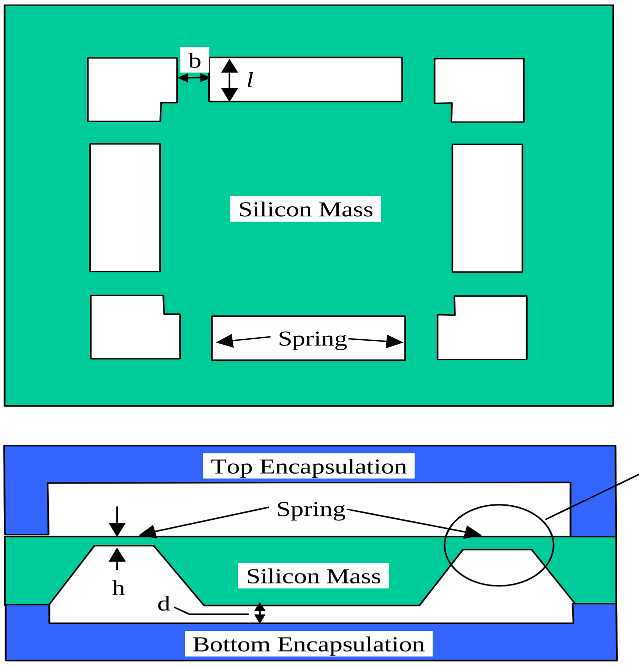

Figure 2. A schematic of the micro accelerometer.

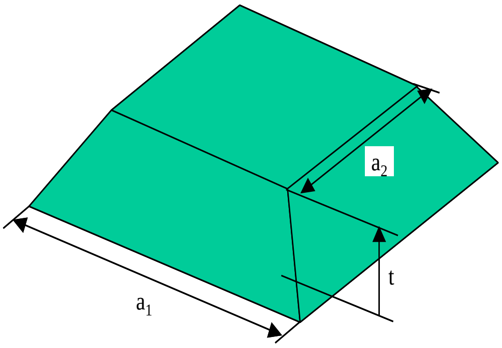

Figure 3. 3-D view of the silicon mass in the accelerometer

III. ACCELEROMETER DESIGN PROCEDURE

In general, for the design of a MEMS device with moving parts, the analysis usually starts with a structural analysis and a vibration analysis. This work focuses on the modeling of the silicon MEMS accelerometer only, which attempts to design a surface micro-machined accelerometer that satisfies the specifications in Table I [3].

TABLE I. Accelerometer Specifications.

Parameter	Design Value
Bandwidth, $\boldsymbol{\omega_c}$	Greater than 4 KHz
Acceleration, a	Smaller than 0.02g
Damping ratio, $\boldsymbol{\xi}$	0.6 < $\boldsymbol{\xi}$ <1.1
Resonant Frequency, f_r	Greater than 1 KHz

Some of the range of parameter geometries used in the design are fixed and cannot be changed due to limitation of existing technology. Therefore, the physical design is restricted by this factor. These parameters are listed in Table II [4].

TABLE. II. Constraints on important Parameters of the Accelerometer Operation.

Parameter	Design Value
Height of the beam, h	$2 \le h \le 10\ \mu m$
Width of the beam, b	$100 \le b \le 300\ \mu m$
Length of the beam, l	$300 \le l \le 600\ \mu m$
Length of upper part of silicon mass, a_1	$1 \le a_1 \le 5\ mm$
Depth of air gap between silicon mass and bottom encapsulation, d	$5 \le d \le 40\ \mu m$

The accelerometer is designed for single axis acceleration detection. Without any external mechanical element, the displacement of the silicon mass attached to the beam will be zero. The design of the accelerometer involves the selection of parameters which are the dimension of silicon mass (a_1), the dimension of the silicon beams (*l*, *b*, and *h*) and the depth (*d*) of the air gap between the silicon mass and the bottom encapsulation. All the calculated dimensions must satisfy the bandwidth, acceleration, damping ratio, and resonant frequency specifications. The micro accelerometer design is to be accomplished by exploring the design parameter space using the following design procedure:

- Characteristics of the silicon mass

$$m = \frac{\rho t(a_1^3 - a_2^3)}{3(a_1 - a_3)} \qquad (1)$$

Where ρ = 2300 kg/m^3 is the density of silicon, **t** = 525 μm is the thickness of the silicon mass, and $a_2 = a_1 - t/\sqrt{2}$

- The spring constant is given by

$$k = \frac{8Ebh^3}{l^3} \qquad (2)$$

- The damping coefficient

$$\beta = \frac{0.42\mu a_2^4}{d^3} \qquad (3)$$

- Natural frequency

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (4)$$

- Damping ratio

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$$\xi = \frac{\beta}{\sqrt{4mk}} \qquad (5)$$

- Minimum measurable acceleration

$$a_{min} = \iota\varepsilon_{min}\omega_n^2 \qquad (6)$$

Where $\varepsilon_{min} = 5 * 10^{-7}$ is the minimum measurable strain of the silicon beams.

- Bandwidth

The bandwidth of the system, ω_c, is given by

$$\omega_c = Y\omega_n$$

Where

$$Y = \sqrt{1 - 2\xi^2 + \sqrt{(1-\xi^2)^2 + 1}} \qquad (7)$$

After selecting a specific values of accelerometer geometrical characteristics and we put into the above derived equations and the following results were obtained: a = 0.01523g, ωc = 13.3899 KHz, ξ = 0.7324. All these values are found to be within the required design specifications.

IV. DESIGN PROCEDURE

The micro accelerometer design is to be accomplished by exploring the design parameter space using appropriate design equations.

The following procedure is suggested.

I. Obtain the necessary design equations. Some of these equations have been given above, while the remaining equations need to be derived.

These equations need to allow the calculation of the following:

  a. The silicon mass.
  b. The damping coefficient within the bandwidth.
  c. The spring constant from beam theory (Young's modulus for silicon is $E = 190\times10^9$ N/m^2).
  d. The minimum detectable acceleration in terms of the minimum measurable strain (also from beam theory).
  e. The cutoff frequency that gives the bandwidth.

II. Make an initial selection of the design parameters.

III. Predict the accelerometer performance using the design equations. In particular, compute the damping ratio, minimum detectable acceleration and the bandwidth.

IV. If the calculated damping ratio, minimum detectable acceleration and bandwidth are in range of the specified performance specifications, the design is completed. Otherwise update the design parameter selection and go back to step 3.

V. SIMULATED RESULTS

Design of the accelerometer involves the selection of parameters which are the dimension of silicon mass ($1 \le a_1 \le 5\ mm$), the dimension of the silicon beams ($300 \le l \le 600\ \mu m$, $100 \le b \le 300\ \mu m$, and $2 \le h \le 10\ \mu m$) and the depth ($5 \le d \le 40\ \mu m$) of the air gap between the silicon mass and the bottom encapsulation .

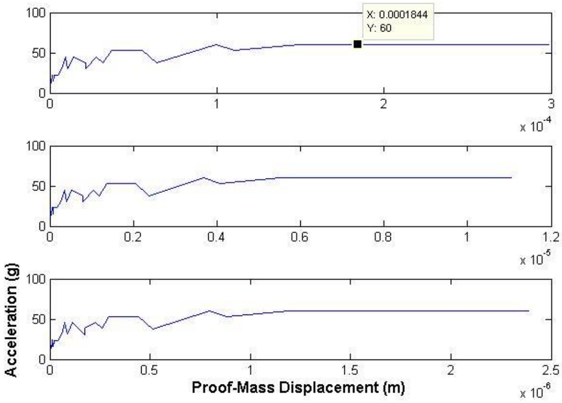


Figure 4 . Relation between acceleration (g) and displacement (m) with specific constraints

VI. ACCELERATION, VELOCITY AND DISPLACEMENT SENSORS

Velocity is the first derivative of displacement vs. time, and acceleration is the derivative of velocity, both measurements can be calculated from acceleration by integrating the signal once or twice or by using the logarithmic relationships between acceleration, velocity, and displacement [5,6] as illustrated below in Figure 5 .

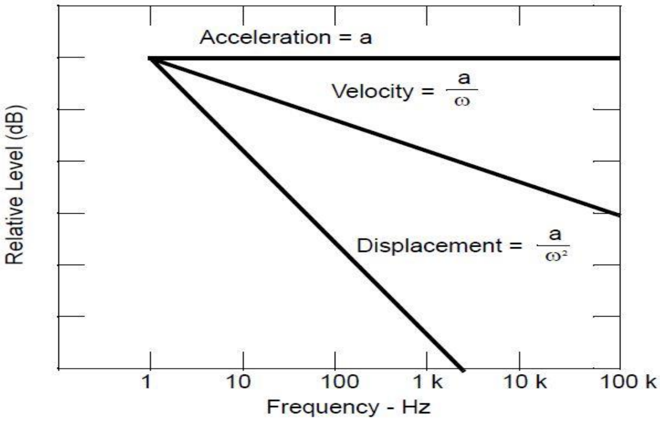


Figure 5. Logarithmic Relationship between Acceleration, Velocity, and Displacement.

$$\text{Acceleration }(m/s^2) = \frac{\text{Change in velocity }(m/s)}{\text{Time taken for change (seconds)}}$$

$$a = \frac{dv}{dt} \quad (a), \quad \text{and} \quad v = \frac{dx}{dt} \quad (b)$$

Then,

$$a = \frac{d(dx)}{dt^2} \quad (c)$$

The integration is the opposite of the derivative.

$v = \int a\,dt$ (d), $x = \int v\,dt$ (e)

Then,

$$\int\left(\int(a)dt\right)dt \qquad \text{(f)}$$

a. Velocity Results From Accelerometer Sensor [7]

$$\text{Velocity} = \frac{a}{\omega}$$

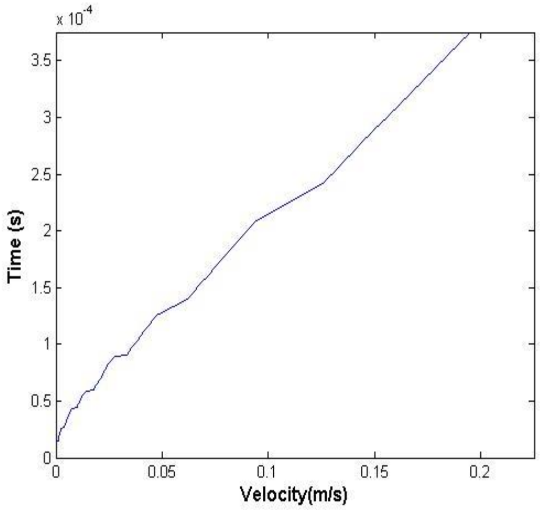


Figure 6. Velocity Obtained from Accelerometer.

TABLE III. Relation between Velocity and Time

Velocity (m/s)	0.2	0.3	0.4	0.5	0.6
Time (ms)	0.4	0.52	0.68	0.85	1.01

b. Displacement Results From Accelerometer Sensor

$$\text{Displacement} = \frac{a}{\omega^2}$$

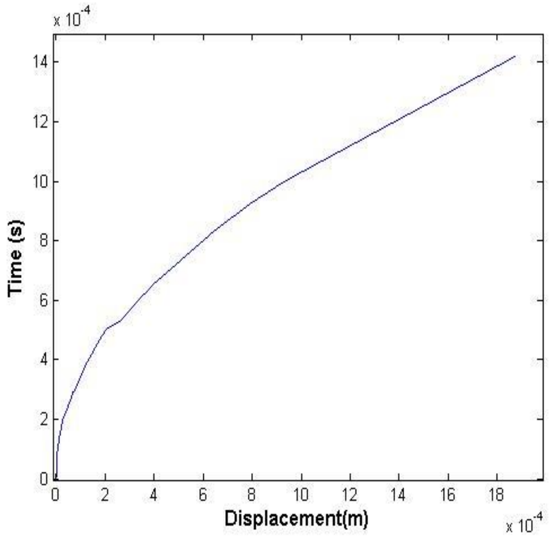


Figure 7 . Displacement Obtained from Accelerometer.

TABLE IV. Relation between Displacement and Time.

Displacement (mm)	0.2	0.3	0.4	0.5	0.6
Time (ms)	0.5	0.57	0.66	0.73	0.8

c. Acceleration and Time

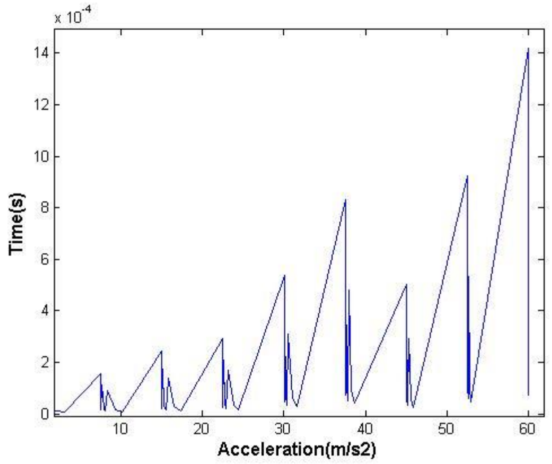
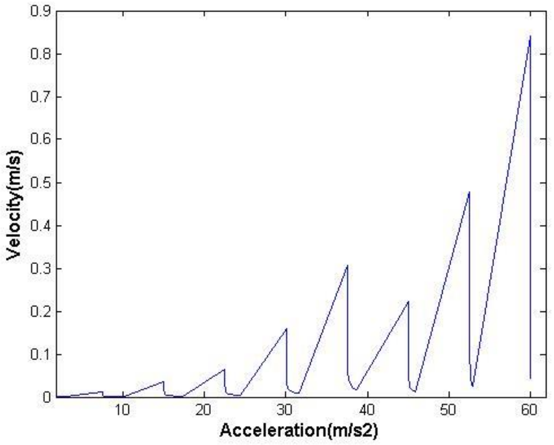


Figure 8. Acceleration Obtained from Accelerometer.

d. Acceleration and Velocity



e. Acceleration and Displacement

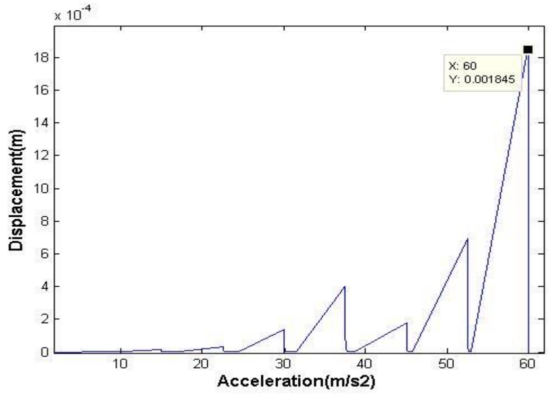


Figure 10. Relation between Acceleration and Displacement.

VII. CONCLUSION

It has been shown that MATLAB software is very important and valuable in determining and optimizing device characteristics, and is thus valuable in the industry. Using the MATLAB software, many modeling tasks in MEMS can be implemented easily. Additionally, their performance can also be determined so that it satisfies the needs of various fields. A complete simulation method for an accelerometer has been carried out. By using this model, a variety of accelerometers with different measurement ranges and cavity depth can be designed. Furthermore, velocity is the first derivative of displacement vs. time, and acceleration is the derivative of velocity, both measurements can be calculated from acceleration by integrating the signal once or twice or by using the logarithmic relationships between acceleration, velocity, and displacement. From the simulation, it can be seen that velocity increases while acceleration is above zero and when acceleration is right at zero, the rate of change in velocity doesn’t change which called "Uniform motion " and after that velocity will varying and become not uniform. Also displacement begins at zero, then increases while velocity is above zero because it takes time for an object to have a displacement.

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