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Sergey Y. Yurish

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Design and Analysis of Bulk Micromachined Piezoresistive MEMS Accelerometer for Concrete SHM Applications

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Abstract: Structural Health Monitoring (SHM) using non destructive testing generally involves measurement of shift in natural frequency of the monitored structure. Vibration sensors play a crucial role in such SHM systems and the present day SHM systems use commercially available off the shelf MEMS accelerometers. In this work, an attempt has been made to design a MEMS accelerometer that is specifically intended for concrete SHM applications. This paper presents the design methodology of a MEMS silicon piezoresistive single axis accelerometer with the seismic mass (m) suspended by four symmetrical cantilever beams. The simulation and analysis results using CoventorWare MEMS design tool show that this newly designed accelerometer is capable of measuring vibrations up to 2 g. The modal analysis results indicate that the accelerometers considered for this analysis (Device-A, Device-B, Device-C) using CoventorWare simulation tool has its first mode natural frequency of 1040 Hz and 946 Hz respectively against the specified 900 Hz. The piezoresistive sensitivity of Device-A (with larger mass and optimum stiffness) is found to be the maximum thus demonstrates that the beam length and half side length of the mass should lie in the region (L<a).

Keywords: Structural health monitoring, MEMS, Piezoresistive, Single axis Accelerometer.

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1. Introduction

Structural Health Monitoring (SHM) involves determination of structural health status of the concrete structures and potentially predicts the damage of the structure. Conventionally wired sensors are installed to manually acquire the vibration data and natural frequency is obtained from the vibration data using FFT analysis. The shift in the natural frequency indicates damage and the magnitude of the frequency shift can be used to quantify the damage levels [1]. This kind of health monitoring is restricted by either the cost of permanently installed sensors or of manual collection of structural data using portable equipment. In the recent past, wireless sensors have been considered as a potential alternative to the wired sensors since it offers a more cost effective approach for capturing the vibration data from the structure.

Even among the wireless sensors being developed, the MEMS vibration sensors are beginning to play crucial role since the sensing and data transmission can be integrated as a single chip. Jerome Peter et al [2] has conducted extensive research on structural health monitoring integrating off-the-shelves accelerometers for sensing the vibration and wireless communication equipment for transmission of acquired vibration data to explore the benefits of wireless structural monitoring systems. To date, the standard practice in the SHM community has been to adapt commercial off-the-shelf (COTS) sensing technologies to the particular proof-of concept experiment at hand. In the recent past, COTS MEMS accelerometers have been used for SHM [2]. Micro electro-mechanical systems (MEMS) sensor is fabricated through micro-fabrication techniques. In MEMS sensors, electro-mechanical transduction mechanisms can be combined with micro-circuitry thereby forming a sensor. The sensor is now a miniaturized version of the traditional transduction element along with substantial circuitry for signal processing and computation [3]. Andreas Vogl et al [4], reported the design and implementation of a novel wireless MEMS Piezoresistive accelerometer sensor with a sensitivity of 0.19 mV/g/V for condition monitoring of AC motors. However, little attention has been paid to the development and implementation of MEMS sensors with the intent of specifically addressing issues related to concrete SHM.

The fundamental building blocks of structural monitoring systems are the sensing transducers. The quality and completeness of the data set collected for a given structure largely depends upon the capabilities and quality of the transducers used to record structural responses. Especially, the MEMS sensors used for concrete structure health monitoring should be of high sensitivity with ultra noise floor since most ambient vibrations in civil structures are characterized by low-amplitude accelerations. Secondly, the natural frequencies of civil structures are relatively small and hence the MEMS accelerometers designed for Civil SHM need not have larger band width. Ultimately, such sensors should be of low cost and consume low power. The authors of this present paper have made an attempt to design a Piezoresistive MEMS accelerometer that satisfies the requirements of an accelerometer meant for concrete SHM applications. The results of such a design and the modal analysis on the designed accelerometer obtained through CoventorWare simulation tool are presented in this paper.

1. 2. Proposed MEMS Accelerometer (Vibration Sensor)

The cross sectional view of the MEMS accelerometer considered in this study for concrete SHM applications is shown in Fig. 1 and the top view of the MEMS accelerometer and view of the structure created for analysis by CoventerWare are presented in Figs. 2 (a) and 2 (b) respectively.

The seismic mass (m) is suspended by four symmetrical beams that determine the stiffness constant ‘k’. This structure with the seismic mass (m) suspended by four symmetrical cantilever beams has been preferred in this study to reduce the cross-axis sensitivity. The other advantage is that device can be realized using bulk micromachining and hence it paves way for using a large mass which is typically required for achieving higher sensitivity at low frequency vibrations. Four silicon piezoresistors strategically embedded on these four beams gives the vibration in terms of change in their resistances. The strategic locations at which these resistors are placed will be discussed in a later section. The four piezoresistors were organized in a Wheatstone bridge to sense single axis (*z*-direction) vibration. Considering the fact that this accelerometer is intended for concrete SHM applications, the device parameters are specified as given in the Table 1.

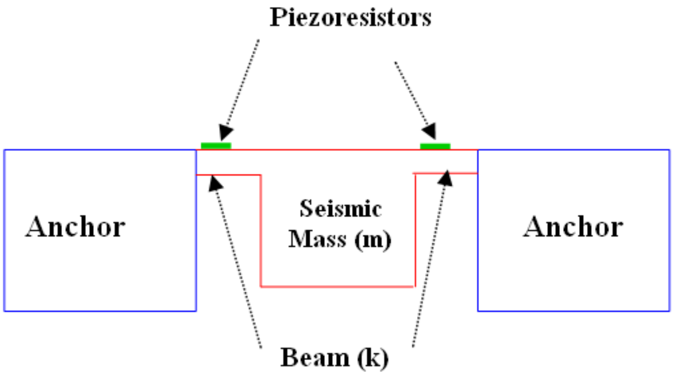


Fig. 1. Cross sectional view of the MEMS accelerometer.

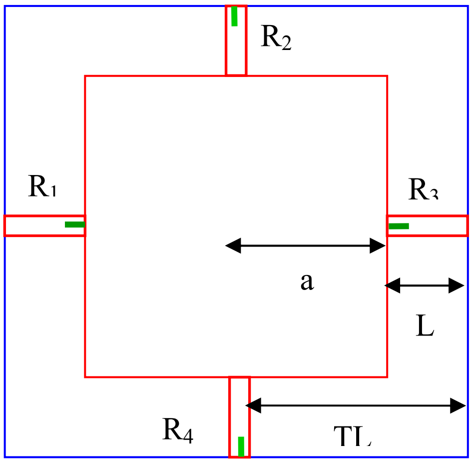


Fig. 2 (a). Top view of the MEMS accelerometer.

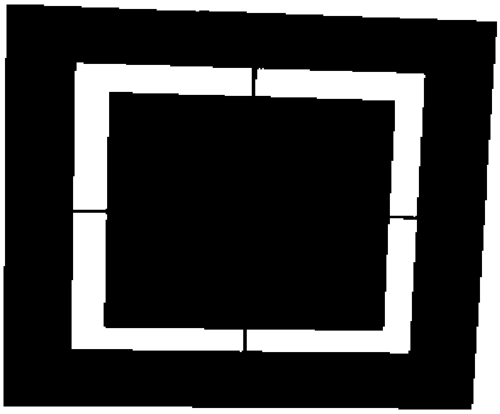


Fig. 2(b). MEMS accelerometer structure created in CoventorWare simulation software.

Table 1. Design specifications of the MEMS vibration sensor.

Parameter	**Specified value**
Acceleration Range	0-2 g
Resonance(Bandwidth)	900 Hz
Sensitivity	1 mV/g/V
Cross axis sensitivity	<5 %

3. Analytical Model for Natural Frequency

The natural frequency of this accelerometer can be estimated from the well known equation

$$\omega_o = \sqrt{k / m} \tag{1}$$

where k is the effective stiffness of the beams and m is the mass of the effective seismic mass and the stiffness constant (k) of the present beam structure is obtained as

$$k = \frac{48EI}{L^3}, \tag{2}$$

where E is the young's modulus of the beam material and the moment of inertia, I is thus

$$I = \frac{1}{12} bt^3, \tag{3}$$

where b and t are the breadth and thickness of a beam respectively. The existing analytical model for natural frequency of such an accelerometer [4, 5] has been given as

$$f_o = \frac{1}{2\pi}\sqrt{\frac{4Ebt^3}{mL^3}} \tag{4}$$

4. Structural Design of the MEMS Piezoresistive Accelerometer Sensor

The main design requirement of an accelerometer with an intended application of concrete SHM is high sensitivity for low frequency vibrations. High sensitivity can be achieved with large mass and lower stiffness. But, large mass and lower stiffness will result in lower resonance frequency and hence lower bandwidth. However, this is a favourable situation while considering an accelerometer for SHM applications since this application typically needs lower bandwidth. The other major advantages of this structure is that it needs no sacrificial etching in realizing the suspended proof mass and therefore the conventional stiction problems faced in the surface micromachined structures are eliminated. Further this structure helps us to realize larger mass unlike surface micromaching where large mass realization may be difficult with thin film.

A brief survey [6, 7] of the literature indicates that the maximum frequency of the excitation signals used for SHM applications is 100 Hz. The natural frequency of the accelerometer in the present study has been fixed at 900 Hz, considering safe design for low noise floor. The next step in this design is to arriving at the required mass and stiffness to achieve this frequency.

4.1. Proof Mass and Beam Length Design

The proof mass design is limited by the maximum die size of the accelerometer within which it is required to realize this structure. The die size is fixed to be 6 mm×6 mm. It is understood from the top view of the accelerometer as shown in Fig. 2(a). That sum of the beam length (L) and half side length of the proof mass (a) is fixed and it is denoted as “TL”. In the present case this TL= 2250 µm. If *L* is increased, *a* is reduced and the right design should determine the value of *L* and *a* so as to get maximum sensitivity which is achieved by placing the resistors in the maximum stress region. It is known that these dimensions are related to the natural frequency since the half side length of the mass (*a*) and beam length (*L*) decide the natural frequency for a given beam thickness and width. The side length of the mass decides the mass (m) and the beam length decides the stiffness (k). Hence the natural frequency is plotted against the beam length. The values of *L* and *a* for the chosen resonant frequency (900 Hz in this case) are obtained from the natural frequency versus beam length plot as shown in Fig. 3.

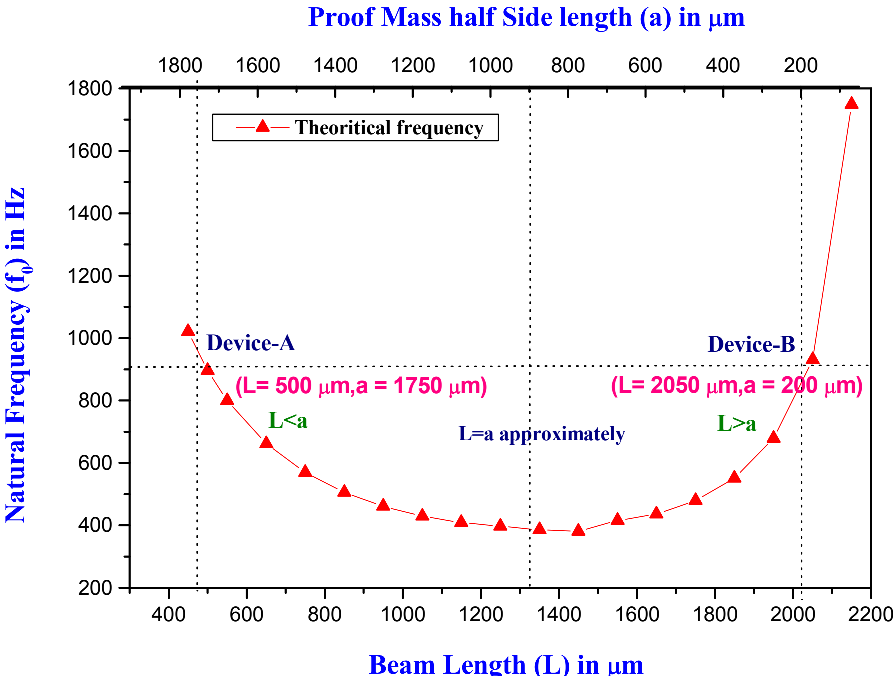


Fig. 3. Natural frequency versus beam length.

It is evident from Fig. 3 that the natural frequency of 900 Hz can be obtained for two different dimensions of the proposed structure viz (*L*= 500 µm, *a* = 1750 µm) and (*L*= 2050 µm, *a* = 200 µm). Hence both structures are considered for detailed analysis to select the best. Based on this analysis, the dimensions of the piezoresistive accelerometers designated as Device-A (*L*= 500 µm, *a* = 1750 µm) and Device-B (*L*= 2050 µm, *a* = 200 µm) of our design are specified as given in Table 2.

Though natural frequency is one of the important design parameter, it is equally important to achieve maximum sensitivity with the piezoresistor for the designed sensor. Hence the determination of *L* and *a* should not only decide the bandwidth or natural frequency but also should result in maximum sensitivity. In order to find the dimensions of the *L* and *a* that provide maximum sensitivity, the displacement in the Z-axis is calculated and plotted using the equation (5).

Table 2. Geometries of the sensor.

Structural parameters	Dimension in µm Device-A	Dimension in µm Device-B	Dimension in µm Device-C
Proofmass half side length (a)	1750	200	900
Proofmass thickness (h)	860	860	860
Beam length (L)	500	2050	1350
Beam width (b)	45	45	45
Beam thickness (t)	15	15	15
Die size	6000 × 6000	6000 × 6000	6000 × 6000

$$\delta = \frac{nmgL^3}{48EI}, \tag{5}$$

where n is the acceleration in g (g = 9.8 m/s^2) , m is the mass of the proofmass, E is the Young's modulus of silicon and I is the moment of inertia.

The calculated deflections are plotted against the beam length and half side length of mass. The deflection obtained using CoventorWare simulation for various L and a is also plotted as shown in Fig. 4 and the values match satisfactory with the theoretical deflection values. The deflection seems to be increasing in the region ($L<a$) where large stiffness and mass (m) together decide the deflection and reaches the maximum at $L \approx a$ (optimum stiffness and mass) and then it decreases as $L>a$ where saturating small stiffness and smaller mass (m) as shown in Fig. 5(a) and Fig. 5(b). A larger 'a' (proof mass half side length) indicates larger mass and large L (beam length) indicates lower stiffness. It is also seen that the maximum deflection is obtained for the case a = 900 µm and L = 1350 µm. Hence it is decided to estimate the sensitivity of this device designated as Device-C also apart from Device-A and Device-B for further analysis and the dimensions for all these three devices are given in Table.2.

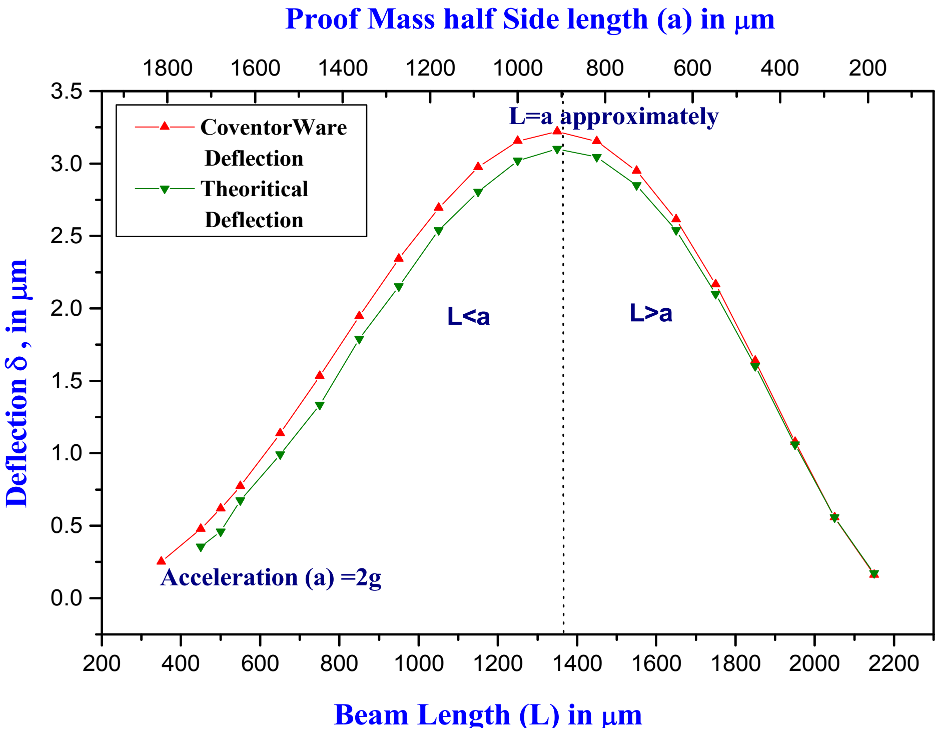


Fig. 4. Beam length versus deflection.

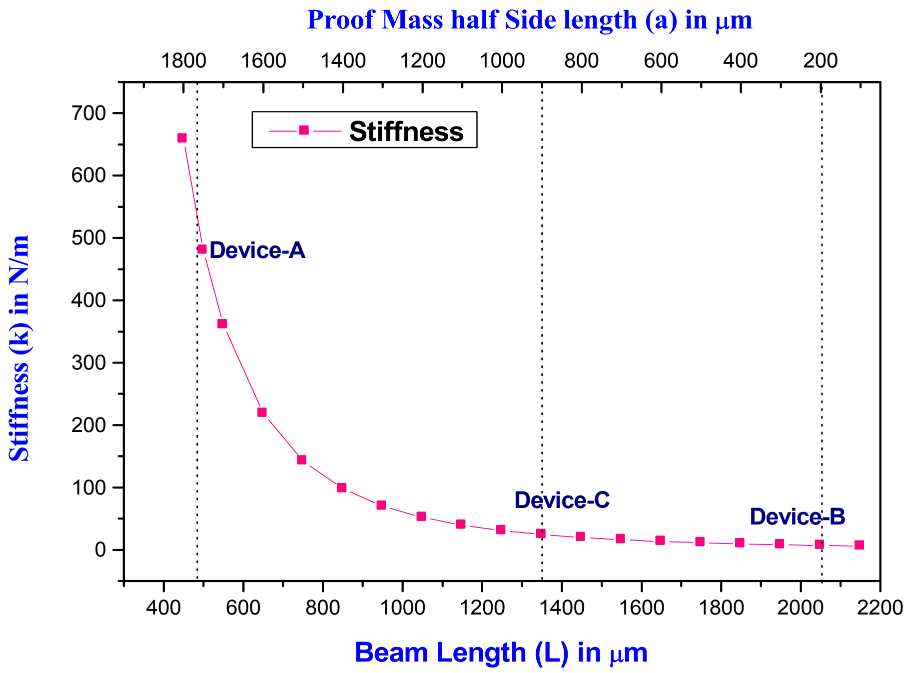


Fig. 5(a). Beam length versus stiffness.

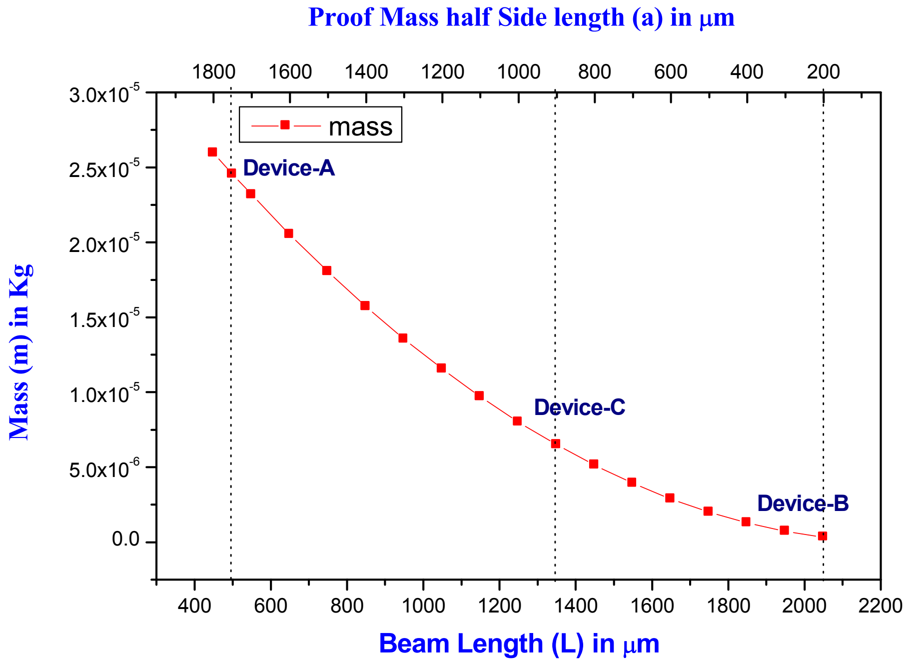


Fig. 5(b). Beam length versus mass.

4.2. Piezoresistor Design

The frame is fixed to the system whose acceleration is to be measured. As the system accelerates, the frame moves with it. The proof mass, due to its inertia tries to remain in its earlier position and in the process gets deflected up and down, depending on the direction of the motion of the system. As a result, stress will be developed at the frame and proof mass ends of each flexure. This stress developed is directly proportional to the vibration or acceleration and exact measurement of this stress will lead to successful measurement of acceleration [8]. Boron doped p-type Silicon piezoresistors are used in this accelerometer to sense the stress and convert this stress into change in resistance. Four piezoresistors are implanted at maximum stress points on each beam as shown in Fig. 2. The resistors R_1 and R_3 experience tensile stress and R_2 and R_4 experience compressive stress when subjected to a positive acceleration (+g). This leads to an increased resistance in the piezoresistors experiencing tensile stress and decreased resistance in the piezoresistors experiencing compressive stress. This condition is reversed in the case of negative acceleration (-g). Surface resistors were selected for achieving high sensitivity [9, 10]. Here the sensitivity of the sensor was maximized by large mass with almost the full wafer thickness, thin and narrow beams as explained in the earlier sections. The zero g resistance is chosen as 1000 Ω. The dimensions of the piezoresistors and other material properties are given in Table 3.

Table 3. Piezoresistor specifications.

Physical parameters of Piezoresistor	**Dimensions**
Piezoresistor length (l)	50 μm
Piezoresistor width (w)	10 μm
Piezoresistor thickness(h)	0.6 μm
Resistivity (ρ)	0.012 Ω-cm
Young's modulus	160 GPa
Poisson's ratio	0.3

The electrical sensitivity *S* for the Wheatstone bridge of boron doped silicon piezoresistors can then be roughly calculated by introducing the effective piezo-resistive coefficient π_{eff}. For the piezoresistors described here, the resistance is given by $R = \rho l / A$, where *l* is the length and *A* is the cross-sectional area of the silicon resistor. Assuming that the dimensional changes can be neglected and that the stress is applied in the longitudinal direction, the change in resistance, ΔR, is given by

$$\frac{\Delta R}{R_0} = \pi_l \sigma_l \text{ for R1 and R3}$$

or

$$\frac{\Delta R}{R_0} = \pi_t \sigma_t \text{ for R2 and R4,} \tag{6}$$

where R_0 is the initial resistance, π_l and π_t are the longitudinal and transverse piezoresistive coefficients respectively, σ_l and σ_t are the longitudinal and transverse stresses respectively. The piezoresistive coefficients are dependent on the dopant concentration, crystal orientation and temperature. At room temperature, the measured piezoresistive coefficients for p-type single-crystal silicon are $\pi_{11} = 6.6 \times 10^{-11}$ Pa^{-1}, $\pi_{12} = -1.1 \times 10^{-11}$ Pa^{-1} and $\pi_{44} = 138.1 \times 10^{-11}$ Pa^{-1}. These values have been used in the CoventorWare simulation and the stress levels experienced by the beam at +2g are plotted against the distance from midpoint of proof mass as shown in Figs. 6 (a) and 6 (b). It is seen from the Fig.6 (a) that R_1 would undergo maximum tensile stress when located at the proof mass end as indicated in the figure (between -1750 μm to -1800 μm in X-axis) and R_3 should undergo maximum tensile stress when located between 1750 μm to 1800 μm in X-axis. Similarly, in order to make the resistors R_2 and R_4 experience compressive stress they are located between 2200 μm to 2250 μm and between -2200 μm to -2250 μm respectively in Y axis as shown in Fig. 6 (b).

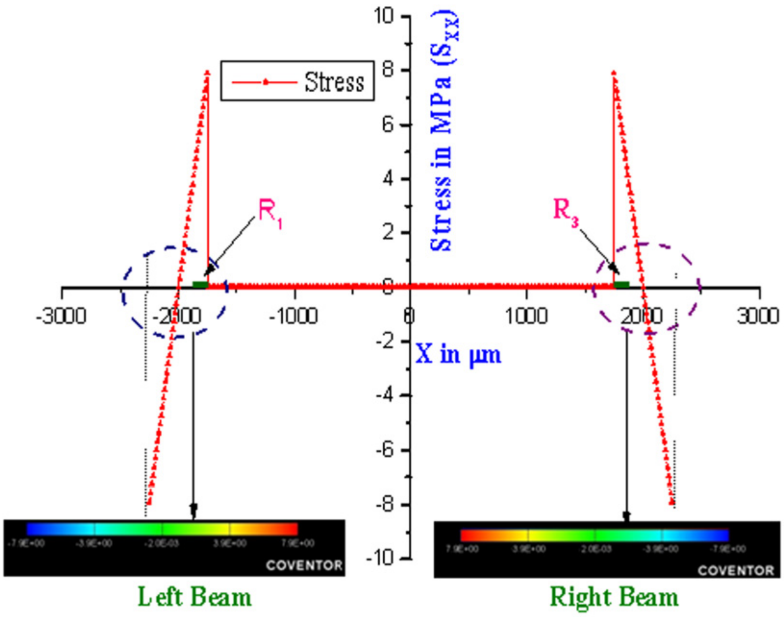


Fig. 6(a). Stress (S_{xx}) at +2g in MPa.

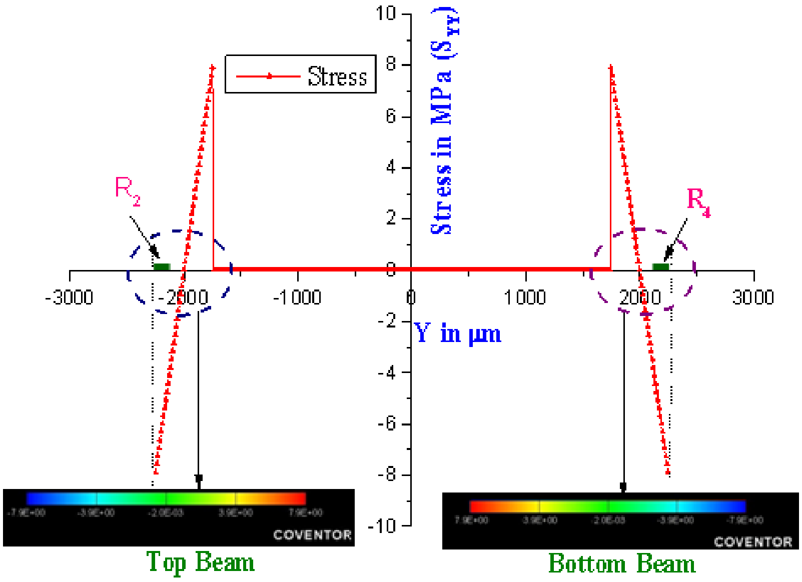


Fig. 6(b). Stress (S_{yy}) at +2g in MPa.

5. Simulation Results and Discussions

These accelerometer structures were analyzed using modules of CoventorWare. Memmech solver has been used for modal, displacement and stress analysis.

5.1. Modal Analysis

Resonance frequency is a function of mass and spring constant and it can be found by performing modal analysis. The modal frequencies of both the devices measured by the FEA analysis corresponding to mode1, mode 2 and mode 3 respectively are given in Table 4 and Mode 1 frequency values obtained using equation (4) and CoventorWare simulation are plotted against beam length as shown in Fig. 7.

Table 4. Modal frequencies.

Mode	Frequency (Hz)		
	Device-A	Device-B	Device-C
Mode 1	1041.1	946.77	401.39
Mode 2	1315.9	2035.9	668.91
Mode 3	1315.9	2035.9	668.91

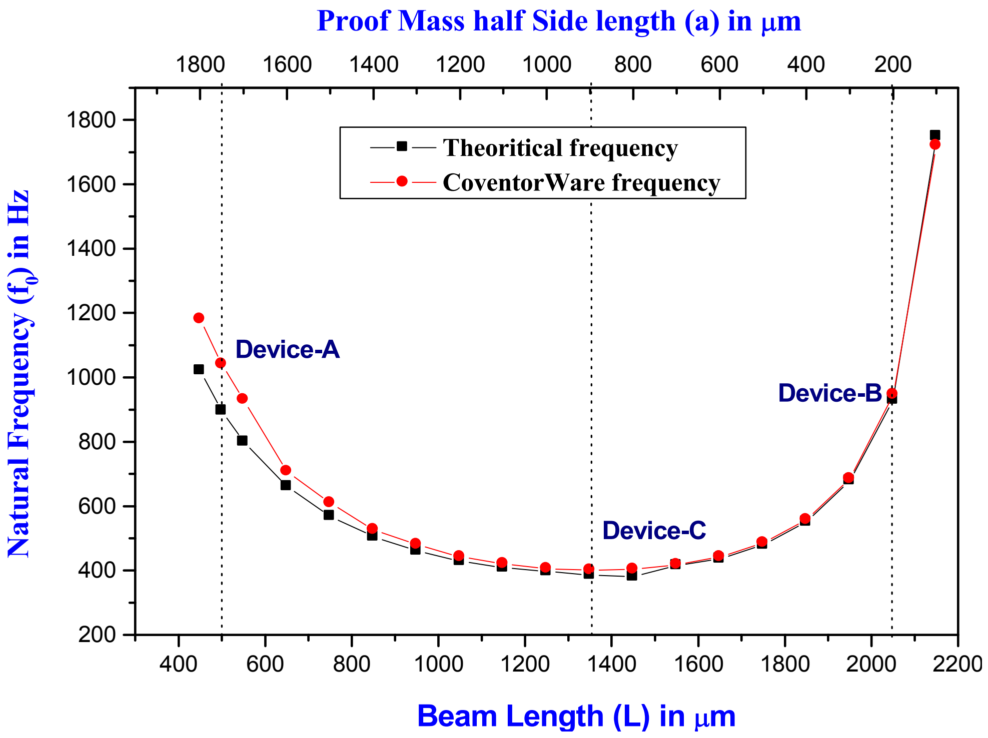


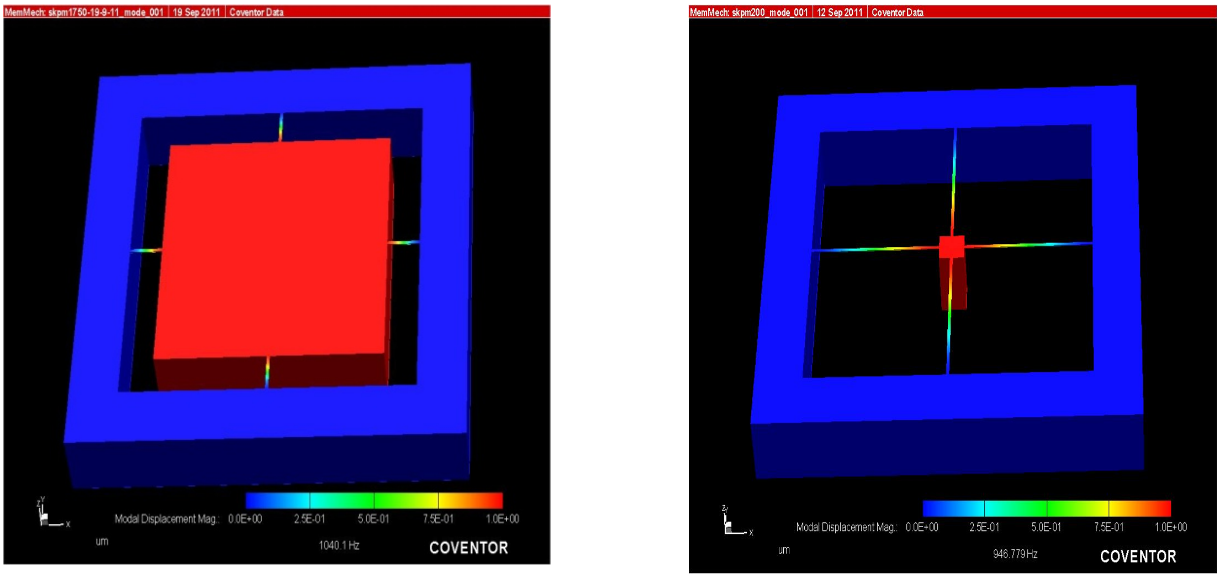
Fig. 7. Beam length versus natural frequency.

The modal frequency (Mode 1) of Device-A and Device-B as estimated by CoventorWare are shown in Figs. 8(a) and 8(b) respectively. Similarly the natural frequency has also been obtained for Device-C.

5.2. Displacement Analysis

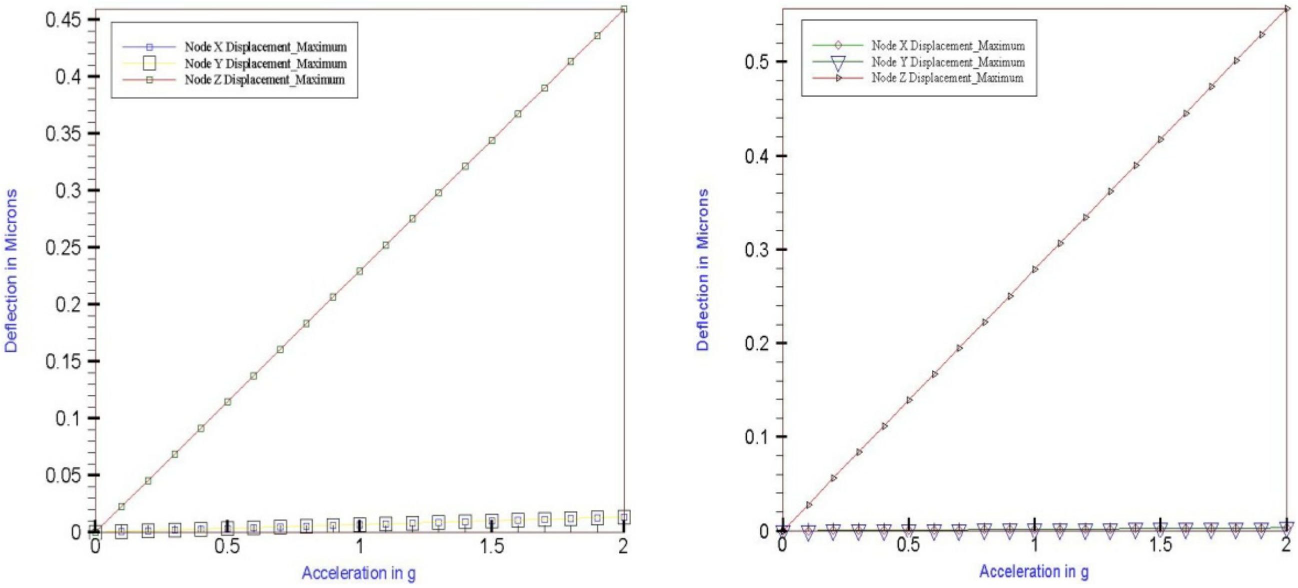
Figs. 9(a) and 9(b) show the displacement using CoventorWare simulation of the two Devices (Device-A and Device- B) for acceleration applied up to 2g. From Figs. 9(a) and 9(b), it is observed that the main axis (Z-axis) deflections are higher compared with the other X and Y axes deflections, indicating that the cross axis sensitivity is reduced in this structure [11]. Similarly the displacement has been obtained for Device-C also.

From Table 5, it is observed that the maximum displacement is obtained for Device-C thus confirming our earlier observation as shown in Fig. 4.



(a) (b)

Fig. 8. Simulation results of modal frequency of Devices: (a) –A, and (b) –B using CoventorWare.



(a) (b)

Fig. 9. Acceleration versus displacement up to 2 g.

Table 5. Displacement results for all the devices.

Device	**Displacement at 2g**
Device-A	0.46 μm
Device-B	0.56 μm
Device-C	3.1 μm

5.3. Piezoresistive Analysis

The change in resistance occurs on each piezoresistor due to applied acceleration. When acceleration is applied, the resistance value of each piezoresistor changes due to piezoresistive effect which in turn changes the Wheatstone bridge output voltage. The bridge output voltage (V_{out}) for 2g acceleration applied in the X, Y and Z-directions for three Devices obtained from piezoresistive analysis are summarized in Table 6.

Table 6. Comparison of Z-direction (main axis) sensitivity for all the three devices at 2g.

Device	**Sensitivity mV/g/V**
Device-A	0.5
Device-B	0.02725
Device-C	0.34

It is also learnt from Table 6 that the voltage sensitivity of Device-B is very less compared with the voltage sensitivity of Device-A and Device-C thus predicting that larger deflection does not yield maximum voltage sensitivity. The cross axis sensitivity has been obtained for Device-A and Device-B. MEMPZR analysis has been used to verify the cross axis sensitivity and the results are listed in Table 7.

Table 7. Comparison of Cross-axis Sensitivity for Both the Devices for 2g.

Device	**Sensitivity for X-axis acceleration, mV/g/V**	**Sensitivity for Y-axis acceleration, mV/g/V**	**Sensitivity for Z-axis acceleration, mV/g/V**
Device-A	0.0035	0.0029	0.5
Device-B	0.000625	0.003	0.02725

It is evident from these results summarized in Table 7 that the main axis sensitivity is high compared with the other axes sensitivity thus demonstrating the ability of this structure to reduce the cross axis sensitivity. The x and y axes sensitivities are 0.7 % and 0.6 % of main axis sensitivity respectively.

5.4. Stress Analysis

Since the maximum voltage sensitivity is not achieved for the devices which have maximum deflection (Device-C) it is necessary to probe the stress values in order to calculate the stress being experienced by various devices being the change in piezoresistance is controlled by stress. The stress is related to the change in resistance (ΔR)

$$\Delta R = \pi_{eff} . \sigma_{\max} , \tag{7}$$

where $\sigma_{\max}$ is the maximum stress and ΔR is the change in resistance. Therefore, the authors calculated the stress for various L and a as done for displacement. It is important to note that the stress is not obtained for the Devices with maximum deflection. This is due to the reason that the stress developed in the beams with very small *L* and large mass (*L*<<*a*) is low and more stress is developed in the beams with *a* larger mass and moderate stiffness (*L*<*a*) (Device-A) rather than lower mass (*L*>*a*) with lower stiffness (Device-B and Device-C). This results coincide with the findings of Andreas et al. [4, 5]. The stress values obtained by FEA simulation also confirm this and the response is shown in Fig. 10.

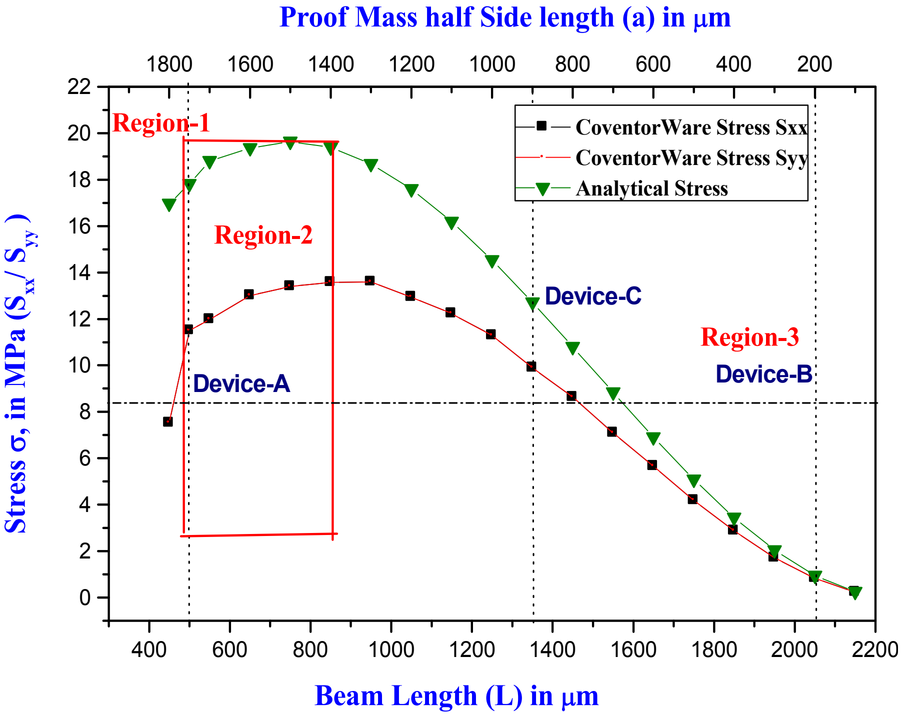


Fig. 10. Comparison of natural frequency and stress for both theoretical and practical.

It is learnt from the stress analysis that there are three regions of operation namely Region 1, 2 and 3 as shown in Fig.10. In the Region-1, the stress levels are low due to high stiffness and large mass (*L*<<*a*). Since the stress levels generated in this region are low, the voltage sensitivity will also be less. In the Region-2, the '*L*' is moderately low compared with '*a*' (*L*<*a*) and therefore large stress levels are seen and hence this region is the most preferred region for achieving larger voltage sensitivity. In the Region-3, the *L* is moderately higher with smaller 'a' (*L*>*a*) or *L* is very high with small *a* (*L*>>*a*). Therefore, the stiffness is smaller than the mass and hence the stress developed in this region is considerably low. So, selection of '*L*' and '*a*' that is falling in this region should be avoided or the resonant frequency of the accelerometer should not fall in this region (*L*>*a*) should be avoided.

Hence it is understood that the beam length should be chosen in such a way that $L < a$. This region is marked by a rectangular box in Fig. 10. It is very important to see that the required f_0 lies in this region. In the other regions where $L \approx a$ or $L > a$ the stress developed is considerably less. This is the reason for larger voltage sensitivity achieved with Device-A compared with Device-B and Device-C.

6. Conclusion

The design and analysis of piezoresistive MEMS accelerometer for concrete SHM applications has been presented in this paper. The analytical model for natural frequency of the MEMS piezoresistive accelerometer whose mass is suspended by four symmetrical cantilever beams was used to design the dimensions of cantilever beam and seismic mass. Silicon piezoresistors embedded in the beams have been designed and placed strategically to achieve maximum sensitivity. Two devices of different dimensions obtained for same resonant frequency and one device with *L≈a* (Device-C) were simulated and analyzed. Comparison of the voltage sensitivity obtained thro piezoresistive analysis in mV/g/V indicates that the structure with large mass and optimum stiffness (*L<a)* is better compared with the one that has lower mass and lower stiffness (*L>>a)*. The Device – A with higher mass and optimum stiffness (*L<a)* gives 0.51 mV/g/V sensitivity in the Z-axis is the highest sensitivity device and it is 0.7 % than the other axes sensitivities. Thus, it is concluded that this structure is ideally suited for single axis accelerometer. The natural frequency of this Device-A is measured to be 1040 Hz and Device-B is measured to be 946 Hz against the design value of 900 Hz.

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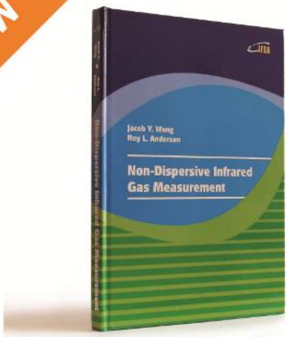
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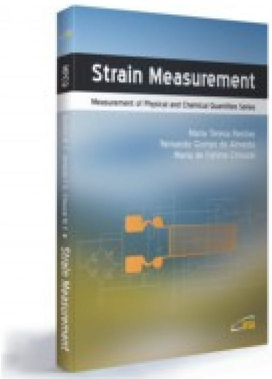
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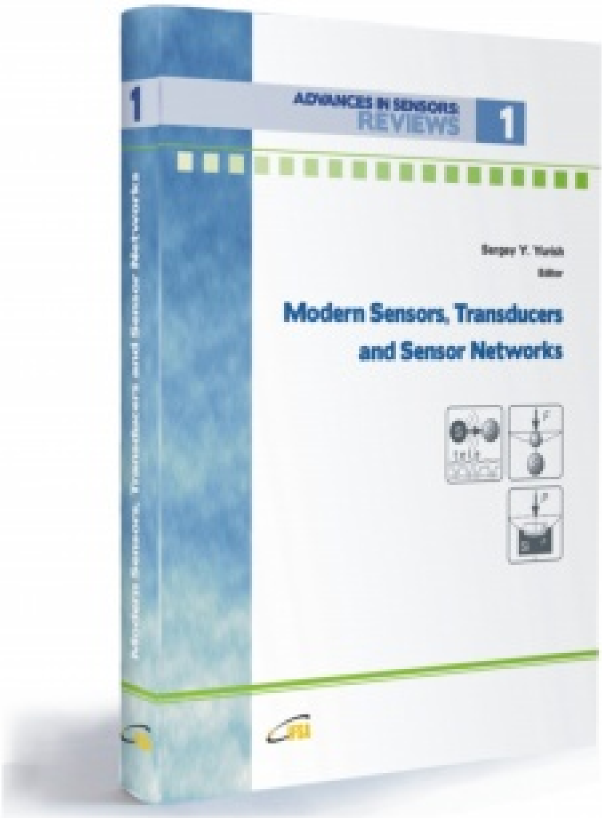
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