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Design of a Shock Immune MEMS Acceleration Sensor and Optimization by Genetic Algorithm

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ABSTRACT

This paper presents a novel capacitive micromachined MEMS acceleration sensor with normal-to-plane shock immunity. The paper takes advantage of suspended cantilevers over the springs of the structure which shorten the spring length for normal movements of the proof mass after a specific distance. Therefore, this makes the springs very much stronger which subsequently prevent more normal movements and catastrophic failures. Also, as the one of the most important parameters of the on-chip devices, which determines the fabrication costs of the devices, consumed area is optimized in this work by genetic algorithm. Modal and several structural analyses are provided in this paper which result very good characteristics for the proposed sensor.

KEYWORD: MEMS, acceleration sensor, genetic algorithm, natural frequency, shock immunity, surface micromachining, and capacitive sensor

1. INTRODUCTION

The state-of-the art navigation systems require high performance acceleration sensors with high shock immunity. Also, acceleration sensing is important in lots of other applications from automotive industries (for airbag control, car suspension control, safety belt), for vibration control of generators and bridges, robotics, geosciences, cell-phones, medical devices, hard disk protection of computers, pacemaker control, security devices, headlight leveling, joy sticks, OCR systems and etc[1].

Various methods have been presented for acceleration sensing with different functionalities, where among them Micro-Electro-Mechanical System (MEMS) technology achieves great deal of interest [2]. Due to their low production cost and uniform production according to batch processing, CMOS compatibility, small size, high sensitivity and resolution, MEMS accelerometers have been successfully commercialized and received the largest MEMS market [3]. Therefore, improving their performance may directly affect their commercial status and open new application(s) for them.

One of the most important problems associated with MEMS accelerometers is their low shock immunity [2] for preventing the device damages. This paper presents a method for protection of the device against unwanted normal-to-plane accelerations.

Another important parameter of all integrated on-chip devices is consumed die area which represents the number of devices on a specific wafer and hence predetermines the cost of the device. For this reason, this paper employs genetic algorithm for minimization of the required die area while considering practical issues of the accelerometer.

Many works have been presented in literature for MEMS accelerometers which are mostly include: surface micromachined capacitive accelerometers [4-6], thermal accelerometers employing thermal convection [7-8], resonant accelerometers [9-10], SOI capacitive accelerometers which employ silicon-on-insulator technique [11], piezoelectric based MEMS accelerometers [12-13] and etc. This paper employs surface micromachined capacitive technique due to its high performances as described in next sections for achieving the best functionality.

The paper is organized as follows; after an introduction in section1, design parameters of the MEMS accelerometer are described in section 2. Die area optimization by genetic algorithm is presented in section 3. The proposed method for normal-to-plane shock immunity of the device is discussed in section 4. Proposed fabrication processes are detailed in section 5. Analysis and simulation results are achieved in section 6 followed by a conclusion in section 7.

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2. DESIGN PARAMETERS OF THE MEMS ACCELEROMETER

There are several fabrication methods for MEMS accelerometers such as surface and bulk micromachining, which each has its own advantages and drawbacks. Also several sensing methods such as capacitive, piezoelectric, resonant and thermal methods have been presented. Among them, capacitive surface micromachining technique is employed in this work due to its high sensitivity, CMOS compatibility, low noise and low temperature dependency [14-15].

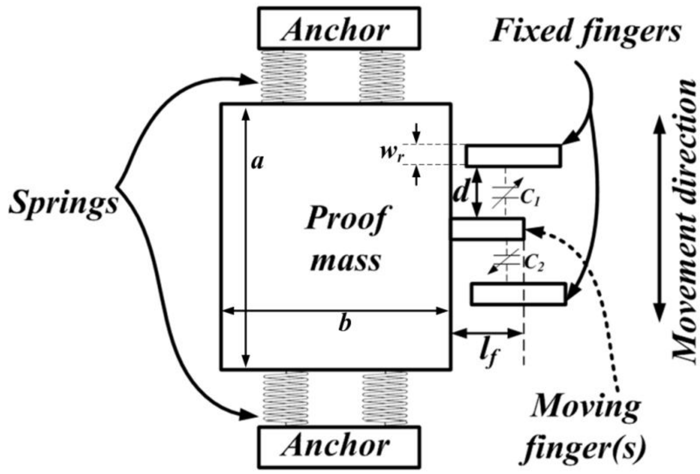

Figure 1. Schematic view of a typical MEMS capacitive accelerometer

Fig.1 illustrates a schematic view of a common capacitive surface micromachined MEMS accelerometer for explains its functionality. The structure is a proof mass suspended above the substrate through 4 springs. Based on mass-spring-damper model, the output displacement versus input acceleration has a second order transfer function given by:

$$\frac{X(s)}{A(s)} = \frac{1}{s^2 + s\frac{\omega_r}{Q} + \omega_r^2} \qquad (1)$$

Where ω_r is the angular resonance frequency of the structure, Q is the quality factor of the sensor and is depends on various parameters such as fabrication deficiencies, squeeze film damping, mode shape and etc.

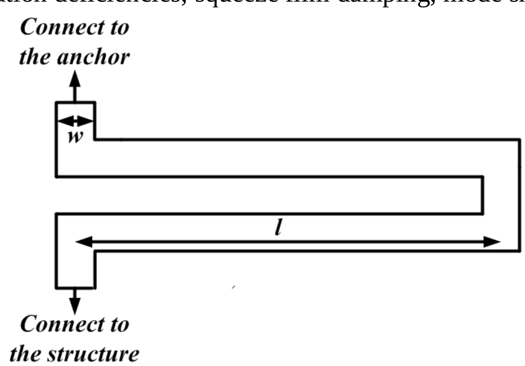

Figure 2. Form of the spring of the sensor

At very low frequencies ($\omega << \omega_r$), the transfer function could be simplified as:

$$\frac{X(s)}{A(s)} \approx \frac{1}{\omega_r^2} \qquad (2)$$

Since, changes in displacement (X) as the result of acceleration (A) is the sensitivity of the device, it can be seen from equation (2) that, the sensitivity increases by decreasing the resonance frequency with a parabolic relation.Like any other mechanical mass-spring-damping system, the resonance frequency of the structure could be calculated by:

$$\omega_r = \sqrt{\frac{k}{m}} \qquad (3)$$

If the applied acceleration has the same frequency as ω_r, the structure starts to oscillate and fails to measure the acceleration. Therefore, $\omega_r$needs to be as high as possible for preventing this failure.Hence, there is a trade-off between bandwidth (the spectrum of measurable incoming acceleration) and sensitivity. For overcoming this problem, the sensing element must be critically damped, i.e.

$$b = 2m\omega_r \qquad (4)$$

Where b is the damping coefficient. For the ease of the fabrication process, there must be some *holes* in the mass of the accelerometer to be discussed in section 5. Therefore the mass of the structure is:

$$m = \left[\left(ab - 16N_{EH}\right) + Nl_f w_f\right]\rho h \qquad (5)$$

Where N_{EH} is the number of 4μm by 4μm etch holes, ρ is the density of the structural material, h is the thickness of the structure and the other parameters are shown in Fig.1. Fig.2 shows the spring of the structure. Since 4 springs are employed for suspension of the structure, they could be considered as 4 parallel springs and therefore, the overall spring constant of the accelerometer is:

$$k_x = 2Eh\left(\frac{w}{l}\right)^3 \qquad (6)$$

Where E is the Young modulus of the structural material (here polysilicon), h is the thickness of the structure and the other parameters are shown in Fig.2.

Another parameter to be concerned is noise equivalent acceleration given by [1]:

$$a_{noise} = \sqrt{\frac{4k_B T\omega_r BW}{Qm}} \qquad (7)$$

Where $k_B$is the Boltzmann constant, T is the absolute temperature and $BW<\omega_r/2\pi$, is the required bandwidth. Another important parameter which determines the resolution of the sensor is overall electrodes to sensor capacitance, given by:

$$C_t = 2\varepsilon_0 N \frac{l_f h}{d} \qquad (8)$$

Where N is the number of these small capacitances and other parameters are defined in Fig.1. Fig.3 shows a typical transfer function of the structure and the critical damped region and operating point of the sensor which could be included in succeeding steps.

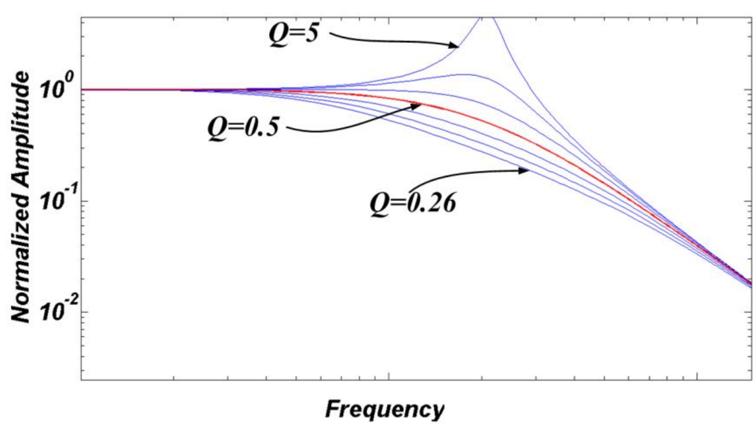

Figure 3. Normalized amplitude versus frequency of the system of equation (1); Q=0.5 is related to critically damped system which is the ideal working point for MEMS accelerometers.

Since the most important source of damping in this kind of resonators is the air damping between structure and electrode fingers, its equation may be useful for our design,

$$b = 7.2\mu l_f \left(\frac{h}{d}\right)^3 \qquad (9)$$

Where μ is the penetration coefficient in air. Dimension optimization of the sensor is discussed in section 3.

3. DIMENSION OPTIMIZATION BY GENETIC ALGORITHM

As mentioned before, consumed die area directly determines the cost of the device. Therefore, its minimization must be concerned as an important problem. But, there is a trade-off between area minimization, resonance frequency and therefore sensitivity. Since, choosing small area means small mass and also shorter and stronger springs which, according to equations (3) and (6), causes increasing the resonance frequency and subsequently, based on equation (2), decreasing the sensitivity. Hence, an optimization is required here.

Genetic algorithm is a stochastic searching technique to find an approximate solution for optimization in computer science. It is a sophisticated method for solving minimization problems like this work. It's a special kind of evolutionary algorithms employing biological techniques such as inheritance and mutation.

Since genetic algorithm is well-known and several standard books such as [16-17] have been published about, for the sake of abbreviation, we skip describing it here and directly describe utilized inequalities and constraints. The optimization goal (fitness function of the genetic algorithm) is minimizing the die area given by:

$$area = \left(b + 2l_f\right)\left(a + 10w\right) \qquad (10)$$

Table1. Design summary of the proposed sensor as the result of optimization by genetic algorithm

Parameter	Value	Parameter	Value	Parameter	Value
a	308µm	*w*	0.5µm	*N*	75
b	115.2µm	*h*	5.7µm	*NEH*	140
l_f	44µm	*l*	96µm	*Area*	61976µm^2
E	160GPa	*ρ*	2320Kg/m^3	C_t	330fF

While considering below inequalities and constraints:

$$\begin{cases} 1\mu m \le l \le \frac{b}{2} + l_f - 5\mu m \\ 0.5\mu m \le w \le 5\mu m \\ 2\mu m \le h \le 10\mu m \\ 100fF \le C_t \\ 10\mu m \le b \le 500\mu m \\ 10\mu m \le a \le 600\mu m \\ 1\mu m \le l_f \le 100\mu m \\ w_f = 2\mu m \\ d = 1\mu m \\ a - b \ge 0 \\ 2000\pi \le \omega_r \le 10000\pi \\ a = 3N\ \mu m \\ \omega_r < \omega_{r,n} \end{cases} \qquad (11)$$

Where $\omega_{r,n}$is the normal-to-plane natural angular frequency to be formulated in next section. Hence the variables are; *a, b*, l_f,*h* and *w*.Results of the genetic algorithm optimization are summarized in table1.

4. NORMAL-TO-PLANE SHOCK IMMUNITY METHOD

Although previously mentioned very good specifications, capacitive surface micromachined MEMS accelerometers suffer from high sensitivity to out-of-plane accelerations and shocks. This is as the result of low thickness of the structure and its springs. Hence, normal-to-plane shocks can cause catastrophic failure and damage of the device.

This paper proposes a method for overcoming this problem and protecting of the device against normal-to-plane shocks and high accelerations. The idea is to put suspended cantileversover the connection points of springs (seeFig.4).

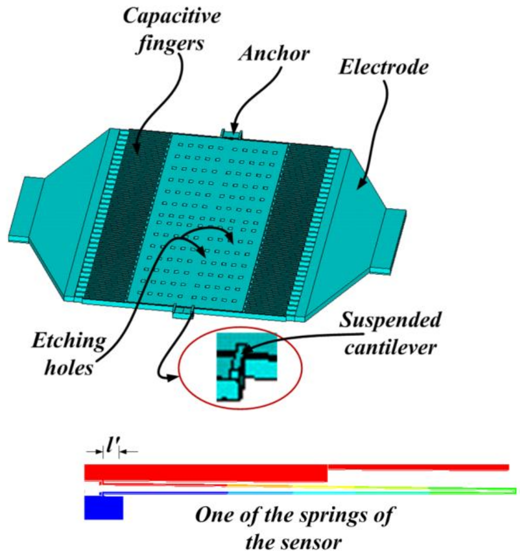

Figure 4. Isometric view of the structure

When the proof mass moves in normal-to-plane direction (due to normal-to-plane acceleration), the spring constant of the structure is relatively low and permits the movement easily. But, as the proof mass comes up, the second part of the spring comes up through with it since touches the cantilever. Now, the contact point acts as a virtual anchor. Hence, the length of the spring becomes very small. This causes a very much stronger spring which won't permit large deflections or movements of the proof mass and subsequently prevents the catastrophic failure.

It is useful to say that, the spring constant of the structure before achieving to the cantilever is:

$$k_z = 2Ew\left(\frac{h}{l}\right)^3 \qquad (12)$$

Because of the mode shape and by considering the design parameters from table 1, this value is about 130 times greater than in-plane vibration mode and therefore, the resonance frequency of the structure in this mode expected to be more than 11 times greater than that of in-plane mode.

It is obvious that, this high resonance frequency cause more immunity to normal shocks itself. The spring constant of the structure after achieving to the cantilever becomes much larger and is equal with:

$$k_z^{'} = 4Ew\left(\frac{h}{l^{'}}\right)^3 \qquad (13)$$

Where *l'* is indicated in Fig.4 and is very smaller than *l*.For this design, the spring constant after achieving to the cantilever becomes more than 15000 times greater than the spring constant before achieving to the cantilever. This very high stiffness puts the resonance frequency from this point forward to far beyond the ordinary applications frequencies around 4MHz and hence solves the out-of-plane shock problem.

5. FABRICATION PROCESS

Surface micromachined capacitive Micro-Electro-Mechanical Systems fabrication process is fully CMOS compatible and hence is an inexpensive technology which takes advantages of fully integration of CMOS transistors read-out circuitry alongside the MEMS sensors.

Fabrication process is outlined in Fig.5 and is include: deposition of a thin adhesive silicon-nitride layer over the silicon substrate. A very thin Cr/Au layer to forming the interconnections is then deposited and patterned. After that, a 1.5μm sacrificial oxide layer is deposited by PECVD and patterned for anchor location. Subsequently, a

5.7μm polysilicon structural material is deposited. Second sacrificial silicon oxide layer is deposited and patterned to open the cantilevers locations.

After deposition and patterning of cantilevers, gaps between fingers of the sensors and electrode and also etching holes are opened by Deep Reactive Ion Etching (DRIE). After all deposition and patterning processes, the whole structure is released to hydrofluoric acid to etch all the sacrificial oxide layers and the final cross-section shown in Fig.5 is achieved.

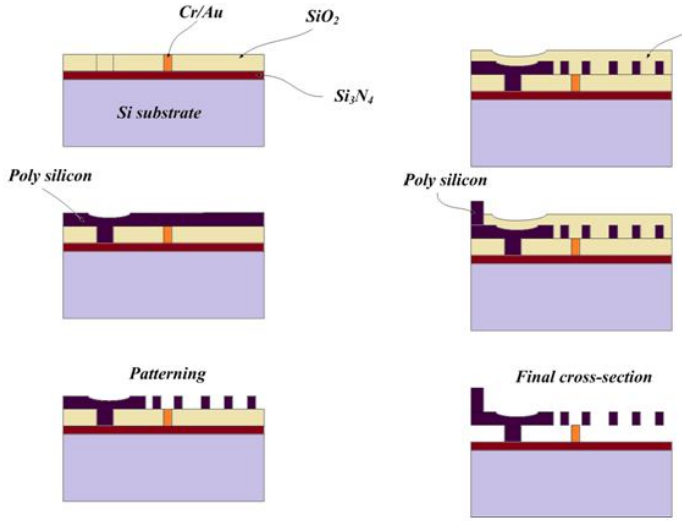

Figure 5. Fabrication process of the proposed structure

6. SIMULATION RESULTS

This section provides several important analysis of the proposed MEMS acceleration sensor. Modal analysis of the structure results natural frequencies of the device both in-plane and normal-to-plane directions as shown in Figs. 6 and 7. It can be seen that, the in-plane natural frequency is 3300Hz and normal-to-plane natural frequency is 34500Hz which has good consistency with discussions in section 4.

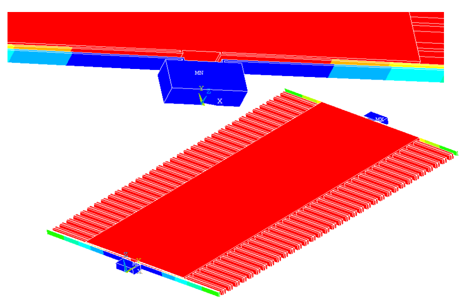

Figure 6. In-plane resonance mode of the structure; note the bending direction of the springs

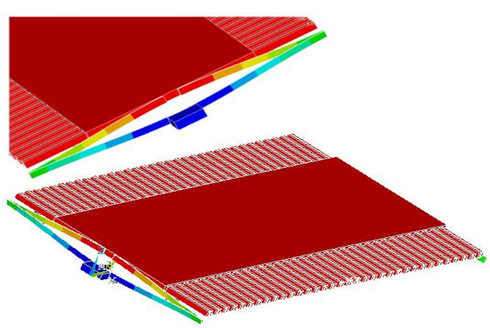

Figure 7. Normal-to-planeresonance mode of the structure; note the bending direction of the springs

Von-Misses stresses are the most important stresses over the structure during its work. They determine the stability of the device. As shown in Fig.8, Von-Misses stress at the in-plane mode of operation for 20g applied acceleration is 0.79Gpa which is 0.49% of the Young modulus of the structural material and therefore has no significant effect over the structure.

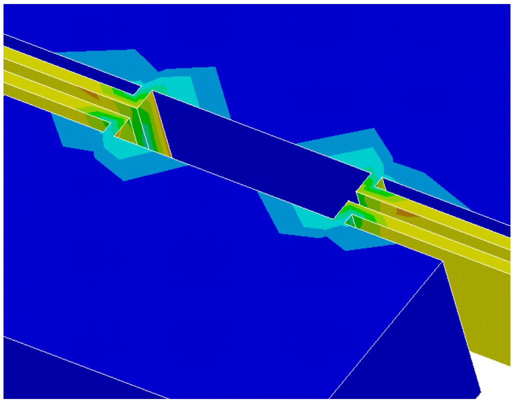

Figure 8. Von-Misses stress of the structure for in-plane acceleration at the springs attachment points (maximum stress points)

Normal displacement of the structure as the result of normal-to-plane accelerations or shocks, causes Von-Misses stresses maximized at the attachment locations of the springs to both the proof mass and anchor. For applied accelerations as high as 36g the Von-Misses profile is look like Fig.9.

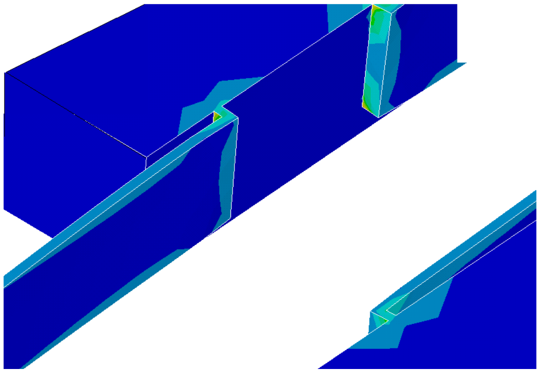

Figure 9. Von-Misses stress of the structure for normal-to-plane acceleration at the springs attachment points (maximum stress points)

Normal-to-plane displacement profile of the structure with cantilever contact is shown in Fig.10. In this condition, the Von-Misses stresses profile of the spring is shown in Fig.11 and Von-Misses stresses of the cantilever in Fig.12.

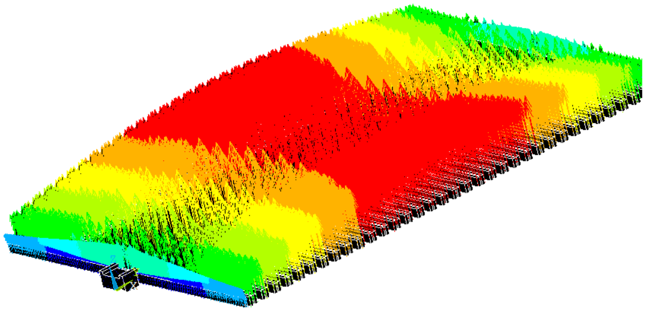

Figure 10. Vector plot of the displacement of the structure with cantilevers as the result of normal-to-plane acceleration

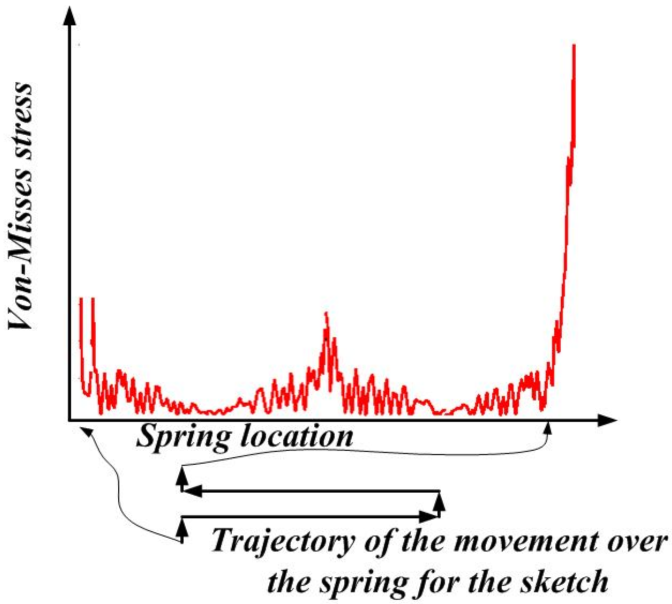

Figure 11. Von-Misses stresses profile for normal-to-plane stresses over the spring

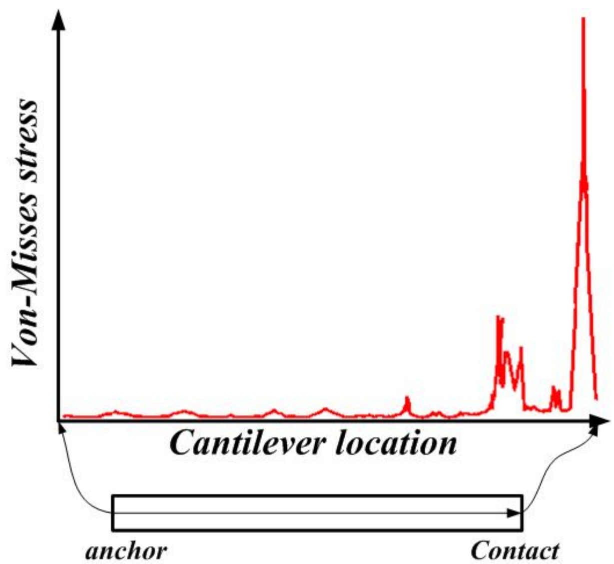

Figure 12. Von-Misses stresses profile for normal-to-plane stresses over the cantilever

The overall data of the designed structure are summarized in table.2. The proposed MEMS surface micromachined capacitive sensor has an optimized area and is very immune to normal-to-plane shocks which is the most important problem associated with this kind of MEMS accelerometer.

Table2. Summary of characteristics of the proposed MEMS accelerometer

Parameter	Value	Parameter	Value
m	*614.1ng*	*k*	0.257N/m
k_z	*33.49N/m*	*k'_z*	2.194MN/m
ω_r(theory)	*20457rad/sec*	*ω_r(FEA)*	20734.5rad/sec
$\omega_{r,n}$(theory)	*233.5Krad/sec*	*$\omega_{r,n}$(FEA)*	212.2Krad/sec
Sensitivity	*7.6nm/g*	*Maximum detectable acceleration*	40g
Minimum detectable acceleration	*0.02g*	*Maximum tolerable normal acceleration without cantilevers*	540g
Maximum tolerable normal acceleration with cantilevers	*2410g*	*Acceleration noise*	0.509mg

7. CONCLUSION

A novel method for improving shock immunity in capacitive surface micromachined MEMS accelerometers have been introduced by employing suspended cantilevers over the structure. The cantilevers were so designed to act as secondary anchors for springs and null a significant part of their lengths. Hence, as springs move upward as the result of normal-to-plane accelerations or shocks, after achieving springs to cantilevers, the spring constant of the structure became thousands times larger which prevented catastrophic failures. Also, the very important die area of the sensor has been optimized by the genetic algorithm to decreasing the fabrication costs of the device. Our researches on performance improvement of MEMS accelerometers are on-going.

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