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Increase of Three-Axis Accelerometer Sensitivity Using Capacitor in Spring Increase of Three-Axis Accelerometer Sensitivity Using Capacitor in Spring

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ABSTRACT: This study has introduced a three-axis capacitive accelerometer, in which the part of the capacitor that calculates acceleration is installed in the z direction in the spring to improve the sensitivity in the said direction. In addition to having the advantages of previous accelerometers, the suggested accelerometer has compensated for previous shortcomings by increasing both sensitivity and pull-in voltage. Moreover, this accelerometer is able to decrease spring torsion and spring nonlinear behavior and provide a more straightforward rigidity computation. Therefore, without increasing the total occupancy level of the sensor, this accelerometer can increase the capacitive planes' surface area to measure acceleration in z direction, resulting in an increase in sensitivity, while all the advantages of previous accelerometers are kept. In designing this accelerometer, factors such as rise time, overshoot, settling time, and peak time were considered. The proposed properties of the accelerometer were also derived from the perspective of a second-order system. Our designed accelerometer showed an operating frequency up to 20 kHz and a dynamic range up to 1000 g. The sensitivity of the accelerometer was 4fF/g in the z axis direction. Moreover, the sensitivity of the accelerometer in x and y directions was 9fF/g.

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1- Introduction

Micro-electromechanical Systems (MEMS) have remarkably expanded the uses of accelerometers in different fields from automotive to biomedical domains [1, 2]. Capacitive MEMS accelerometers can lower power dissipation, production costs, temperature coefficients, IC integration, and MEMS feasibility. Having these merits, the capacitive sensing-based MEMS accelerometers are extensively employed and accepted in the MEMS markets [3]. Based on the MEMS technology, this study has introduced a 3-axis accelerometer with high dynamic range, high operation frequency, and high sensitivity with a low level of occupancy.

Different structures of capacitive accelerometers such as comb-tooth, torsion, cantilever, and sandwich structure have been reported in the literature [4]. The ION Company developed a seismic-detection capacitive accelerometer at $-40\,to\,50^{\circ}C$ with low-frequency performance, the structure of which is made of 4 independent single crystal lithographic silicon wafers. The Middle East Technical University of Turkey introduced a comb-type capacitive accelerometer on the basis of the TSV packaging technology with a 9.45-kHz working frequency and a 1.6pF/g sensitivity, which was widely used in geological examinations owing to its high sensitivity; however, it easily failed in high-impact environments [5]. A 3-axis accelerometer that did not identify the acceleration direction was suggested by [6]. In order to reach a sensitivity of 3fF/g and an acceleration of 1000g in the z direction in this accelerometer, a minimum dimension of 850*850um was required for under-the-weight plane. The condition was satisfied through appropriate spring designing. The main problem in [6] was estimating the acceleration in x and y directions with a very low sensitivity caused by the capacitance change due to the change in the overlap section. For instance, for a displacement of 1um, a change of about 2% in the capacitor value occurred, and to have a 3fF/g sensitivity only an acceleration of 20g was calculable. Moreover, this accelerometer failed to distinguish between the accelerations different axes and could not identify the axis direction of a used acceleration. In [7], a 3-axis accelerometer structure with 3 different accelerometers was reported, in which the three distinguished sections were around 0.4mm2 surface area. Concerning the required space for spring installation, it was possible to exploit a capacitor plane of about 500*500um in z direction. As regards to the 3fF/g sensitivity, the maximal measurable acceleration sensitivity is 450g. It can similarly be corroborated that the acceleration in [7] could not be met along the other axes.

Authors in [8] reported a novel structure, having a maximally 1000g dynamic range and a 20 kHz limit of working frequency. The accelerometer sensitivity was 4fF/g in the z direction and 9fF/g in the x and y directions. In addition, this scheme showed a proper occupying level, which is unprecedented in earlier 3-axis accelerometers. Our proposed struc-

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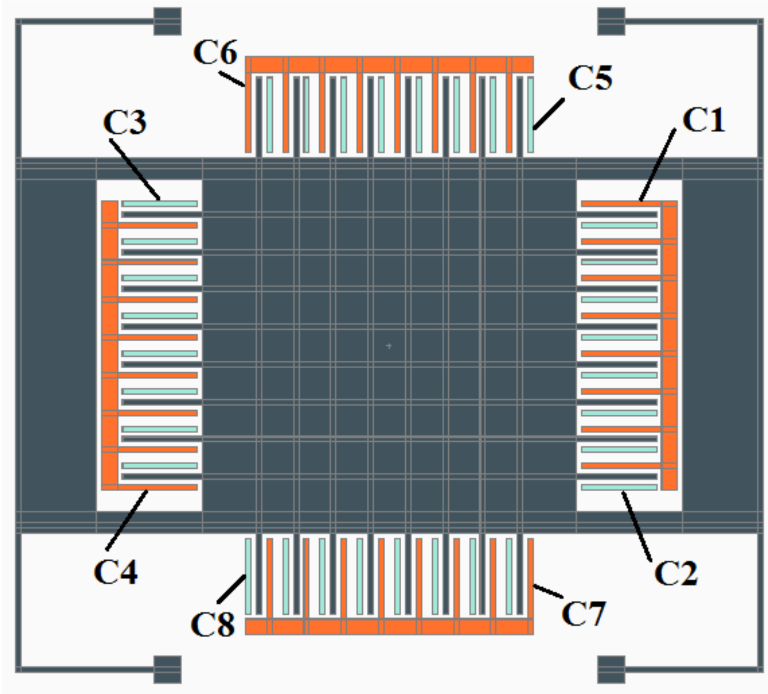

Fig. 1. The suggested scheme in this study

ture also measured accelerations separately in the 3 directions of the axes. The acceleration of each axe had a zero effect on the values of the other two axes' accelerations.

Based on the aforementioned, it is clear that the proposed accelerometer in [8] has specific features that rare in other accelerometers. Nevertheless, its main disadvantage is its low sensitivity in the z axis direction. In our work, it is sought to solve this problem while observing the advantages of [8]. Therefore, an innovative accelerometer with a higher sensitivity in the z axis direction is designed here. The proposed accelerometer has a higher pull-in voltage and a higher sensitivity. Moreover, the spring torsion is lowered, spring rigidity calculation becomes simpler, and nonlinear behavior of the spring is reduced.

The rest of this work is arranged as follows. In section 2, the proposed structure is presented. Section 3 is about designing the dimensions of the elements in the suggested scheme. In section 4, other properties of the designed accelerometer are calculated. The simulation results are given in Section 5.

2- Presentation of the Suggested Structure

There are three parallel planes in the z direction [8]: two are fixed and the third and the middle are mobile. By making a difference in the capacitance measurement, the two parallel upper and lower planes can minimize the effect of noise on the obtained value. Therefore, the scheme in [8] is capable of measuring acceleration in x and y directions. When a y-direction acceleration is applied, the mobile plane and combs will move in the imposed acceleration direction. Hence, increasing the values of capacitors C1 and C3 in the presence of a small air gap but decreasing the values of C2 and C4.

Therefore, when exerting acceleration to one axis direction, a zero effect is imposed on other axes. For instance, by imposing acceleration on the set in the x direction, the values of capacitors C5 and C7 grow (by reducing air distance between 2 planes), but the values of C6 and C8 decrease. Consequently, a shift from zero to a positive value occurs in the case of Cx in terms of the exerted acceleration. The positive value also indicates that the acceleration is in the positive x direction. A question concerning Cy value might arise as well.

In addition to combining the capacitors above, this structure involves 4 parallel springs, each with 2 spring series. For the 8 springs, the total rigidity can be equated into a single spring in the calculations. The spring rigidity is calculated separately for x, y, and z directions.

Based on the said properties, the suggested accelerometer in [8] had a dynamic range up to 1000g and an operation frequency up to 20 kHz. The accelerometer sensitivity is 4fF/g in the z direction and 9fF/g in x and y directions. In addition, this scheme showed a proper occupying level, which is unprecedented in the previous 3-axis accelerometers. Our proposed structure also measured accelerations separately in the direction of the 3 axes. The acceleration of each axe had a zero effect on the values of the accelerations of the other two axes.

As is observed, the accelerometer in [8] is more advantageous than other previous accelerometers; however, it largely suffers from a low sensitivity in z direction. It is sought to increase sensitivity in the z axis direction, while maintaining the advantages of the accelerometer in [8].

As shown in Fig. 1, in this new scheme a part of the capacitor that calculates acceleration in z direction is mounted

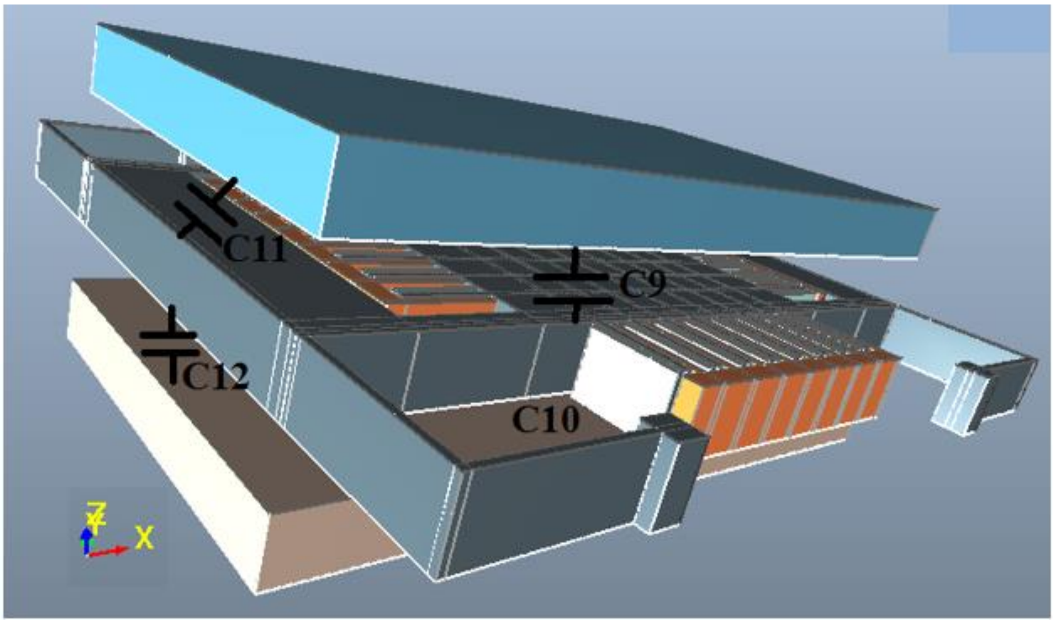

Fig. 2. Side profile of the suggested scheme

on the spring. By doing so, without increasing the total occupying level of the sensor, the capacitive plane areas for measuring acceleration in the z direction increased. As a result, the sensitivity in the z direction improves while all the advantages of the accelerometer in [8] are observed. In fact, capacitors C11 and C12 are added in the z direction. The value of capacitor for measuring acceleration in this direction is as follows:

$$Cz=C9+C11-(C10+C12) \tag{1}$$

where C9 and C10 are capacitors between the pending central mass and the fixed lower and upper planes, respectively. C11 and C12 are capacitors between the installed plane in the spring and the fixed lower and upper planes of accelerometer, respectively. Fig. 2 shows the lateral profile of the suggested scheme involving the 3 layers that make the acceleration-estimating capacitors in the z axis direction.

Note that as compared to [8], no change has occurred in the capacitive values in y and z directions. Therefore, since the weight of the pending mass has increased, if the numerical value of the spring constant increases by the same proportion, then the increased sensitivity will not affect the other characteristics of the accelerometer (e.g., working frequency, dynamic range, etc.).

3- Designing the Dimensions of the Elements in the Suggested Scheme

By observing the advantages of the accelerometer in [8], the problem statement, design requirements, and properties are as follows:

$$ma = kx \tag{2}$$

Problem statement: This study has sought to design a three-axis capacitive accelerometer with high sensitivity to measure acceleration from -1000g to +1000g, cover a frequency range up to 20 KHz, and maintain the desired occupancy level of $1mm^2$. As far as we know, this work is the first study on designing such an important and comprehensive accelerometer.

Designing requirements: two groups of requirements are taken into account, industrial (our accelerometer has been ordered by an Italian company), and practical implementation. These requirements are represented in Tables 1 and 2.

Table 1. Industrial requirements for designing the suggested accelerometer

Parameter	Value
Acceleratio	1000 g
Sensitivity	5fF/g≤
Frequency	20 KHz

Table 2. Practical implementation requirements and limitations in designing the suggested accelerometer

Parameter	Value
Air gap (d)	$1\mu m$
Capacitive plane displacement	Max. d/3
Maximum thickness of weight	$50\mu m$
Maximum length of combs	$150\mu m$

Considering the above requirements, the desired accelerometer designing is described below.

To maintain the advantages of the proposed scheme in [8], size of the combs central weight is assumed to be equal to [8]. Therefore, the spring constant must be in a way that the weight displacement, under an acceleration of 1000 g, is equal to d/3 or about 0.3μm. Since the central weight mass is 58.4 μg and the weights on the two sides are 25 $1\mu g$ in the sum, the total weight of the pending mass is 83.4 μg. Therefore, spring constant can be calculated as follows:

Where m is the weight mass, a is the maximum acceleration of 1000g, and x is displacement that is equal to 0.3 μm for maximum acceleration. Hence, the spring constant will be 2780. It can be observed that the value of the spring constant in our scheme is larger than the previous scheme, which is an advantage since the need for spring arms of great length has been removed and the spring constant can be satisfied using shorter arms. Moreover, by shortening the spring constant, a lower width can be chosen (the required robustness against breakability is provided), hence the spring lengths can be considerably shortened.

On the other hand, increase in spring rigidity in our scheme results in increase in the pull-in voltage value, hence providing a higher safety margin against capacitive break which is also another advantage of our proposed scheme. Other characteristics of the designed accelerometer involving peak time, settling time, overshoot, rise time, and pull-in voltage are extracted.

4- Calculation of Other Characteristics of the Designed Accelerometer

To find the step response of the system unit, first the transition function is multiplied by Laplace transform of unit step function, namely 1/s, thus:

$$Y(s) = \frac{1}{s}\,H(s) = \frac{1}{s}\,k\frac{\omega_0^2}{s^2+2\omega_0\xi\, s+\omega_0^2} \tag{3}$$

Where ω_0 is natural frequency in terms of $\frac{rad}{sec}$, ξ is damping ratio (no unit), and K is system gain. Therefore, the system step response is expressed as follows:

$$y(t) = L^{-1}\{Y(S)\} = L^{-1}\left\{\frac{1}{s}\,H(s)\right\} \tag{4}$$

Depending on the value of the damping ratio, the step response can be obtained in different modes. For instance, the system diagram in the slow damping mode (Eq. 5) can be given as in Fig 2:

$$y(t) = k\left(1 - \frac{1}{\sqrt{1-\xi^2}}e^{-\xi\omega_0 t}\sin\left(\omega_0\sqrt{1-\xi^2}t+\theta\right)\right), \theta = \text{acos}\,(\xi) \tag{5}$$

The properties of rise time, peak time, overshoot, and settling time are very important in the system step response. In general, the desired conditions for a response with fast rising, settling, and low overshoot are as follows:

The tr, Mp, tp, and ts must be small. However, satisfying all these conditions is impossible since a reduction in tr, for example, results in an increase in Mp. Therefore, it is here sought to extract the most important characteristics of the accelerometer against a step response from the perspective of a second-order system. These characteristics are peak time, settling time, overshoot, and rising time, as given in table 3.

Here, $\omega_n = \omega_0$ is the natural frequency of the system, m shows mass, and c signifies capacitor in accelerometer system. In table 3, the values of m, K, c, and hence $\omega_n = \omega_0$ are defined (the defined parameters values are given in the third section of the paper), while other parameters such as ts, Mp, tp, tr, and ξ are unknown.

5- Simulation Results

In this section, simulation of the designed accelerometer in Intellisuite software is described and pull-in voltage of the accelerometer is later extracted through the simulation. The output of software simulation of this accelerometer is shown in Fig. 3. According to this figure, by imposing an acceleration of 1000g in the z direction, the displacement value is 0.23 µm.

Table 3. Other parameters pertaining to the designed accelerometer

Parameter	Equation	Calculated Value
Rise time (tr)	tr≈1.8ωn	10392.304
Settling time (t_s)	$t_s \approx \frac{3}{\sigma}, \sigma = \xi\omega_0$	0.052
Peak time(t_p)	$t_p = \frac{\pi}{\omega_d}, \omega_d = \omega_0\sqrt{1-\xi^2}$	5.44
Overshoot(M_p)	$M_p = \exp\left(-\frac{\pi\xi}{\sqrt{1-\xi^2}}\right)$	23.09
Damping coefficient (ξ)	$\xi = \frac{\frac{c}{m}}{2\sqrt{\frac{k}{m}}}$	0.01
Natural frequency (ω_0)	$\omega_0 = \sqrt{\frac{k}{m}}$	5773.502

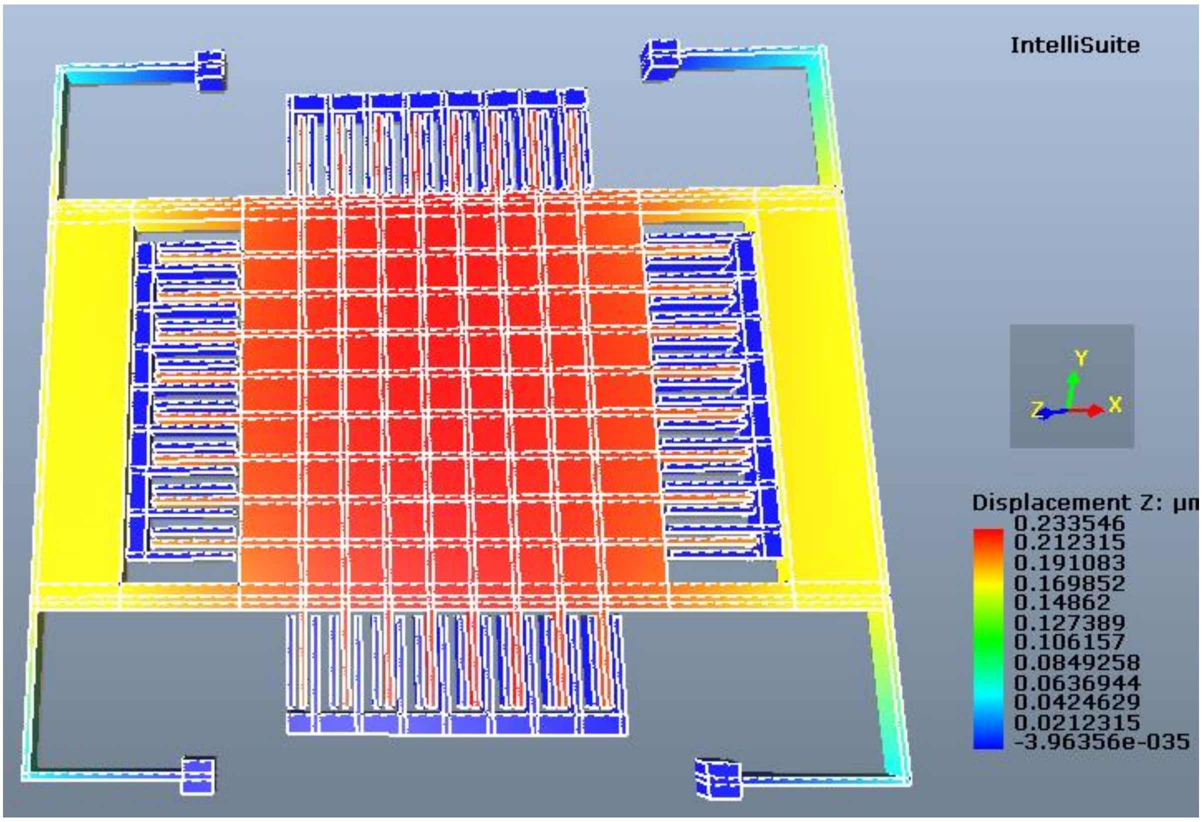

Fig. 3. Simulation of the designed accelerometer using Intellisuite software

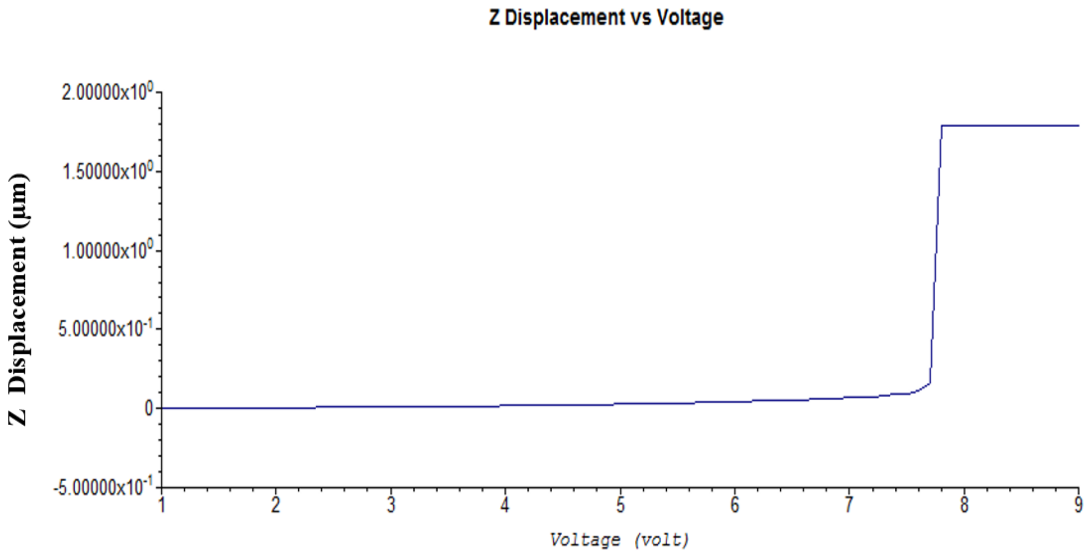

Fig. 4. Pull-in voltage value in [8]

To calculate the pull-in voltage, the following equation can be employed:

$$V_{PI} = \sqrt{\frac{8k_m}{27C_0}}x_0 \quad (6\text{-})$$

Here, first the pull-in voltage in [8] is obtained, which is subsequently compared with the pull-in voltage value obtained in the present study. According to [8], by substituting the values of the spring constant kz = 1827 and the initial value of the capacitor Cz0 = 8.8500e-06 into Eq. 6, and due to the fact that failure occurs in a voltage where the mobile plane of the capacitor has passed a distance of about one third of the initial distance between the two planes, the amount of pull-in voltage in [8] will be Vp = 7.7165v. Up to now, the pull-in voltage value is obtained through an analytical relation. However, the pull-in voltage can also be calculated using the Intellisuite Software by applying a variable voltage to the suggested accelerometer, the amount of displacement is examined and the voltage at the instant when displacement suddenly changes is the pull-in voltage – as shown in Fig. 4.

In this way, the pull-in voltage value is also obtained for our designed accelerometer, which the results are given in Figs. 5 and 6. It can be observed that the pull-in voltage in this work is greater than in [8]. According to Fig. 5, the pull-in voltage value is about 71v. The pull-in voltage of the capacitors forming the accelerometer is high, causing the processing circuit to send voltage signal to the capacitors and receive it with a higher safety margin. Note that for measuring the acceleration, a processing circuit must measure the amount of capacitor changes, which are completely dependent on the applied acceleration, instant by instant.

Moreover, when the acceleration is applied to the accelerometer, the value of the pull-in voltage changes. If the applied force is in the same direction as the electrostatic force of the voltage applied by the processing circuit due to the acceleration, then a decrease of about 58v occurs in the pull-in voltage value, shown in Fig. 5. If the applied force is in the opposite direction of the electrostatic force due to the voltage and acceleration, an increase occurs in the pull-in voltage compared to the initial state.

Table 4 makes a comparison between our designed accelerometer and some previous accelerometers.

6- Conclusion

This study is an attempt to increase the sensitivity of the accelerometer used in [8] in the z axis direction. In designing this accelerometer, new advantages are also introduced while maintaining the advantages and removing the disadvantages of [8]. The accelerometer designed in the present study has the following characteristics:

1. Its sensitivity in z direction has increased by 5.57.
2. The increase of spring rigidity in our scheme led to the increase of the pull-in voltage value; therefore, a higher safety margin against capacitive break was obtained, which is an advantage of our proposed scheme.
3. Spring torsion was reduced, a more straightforward calculation of the spring rigidity was provided, and nonlinear behavior of the spring was better controlled.
4. The accelerometer had a dynamic range up to 1000 g and an operating frequency up to 20 kHz. The accelerometer sensitivity was 4fF/g in z direction, and 9fF/g in x and y

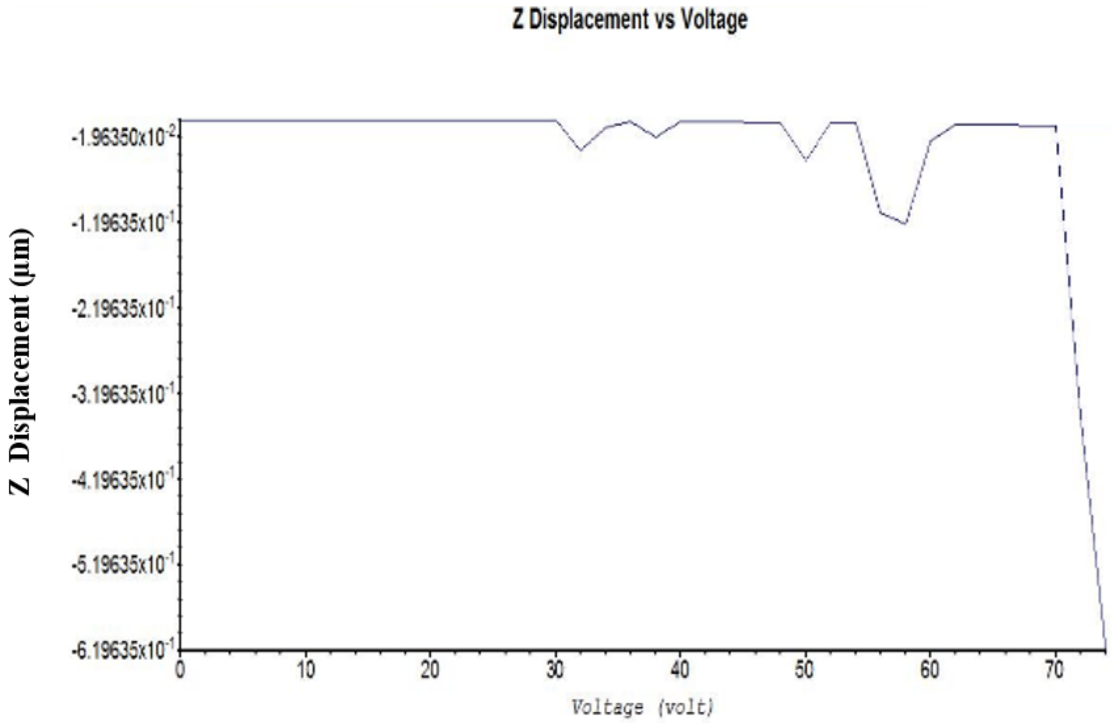

Fig. 5. Pull-in voltage value in our designed accelerometer (acceleration 0g)

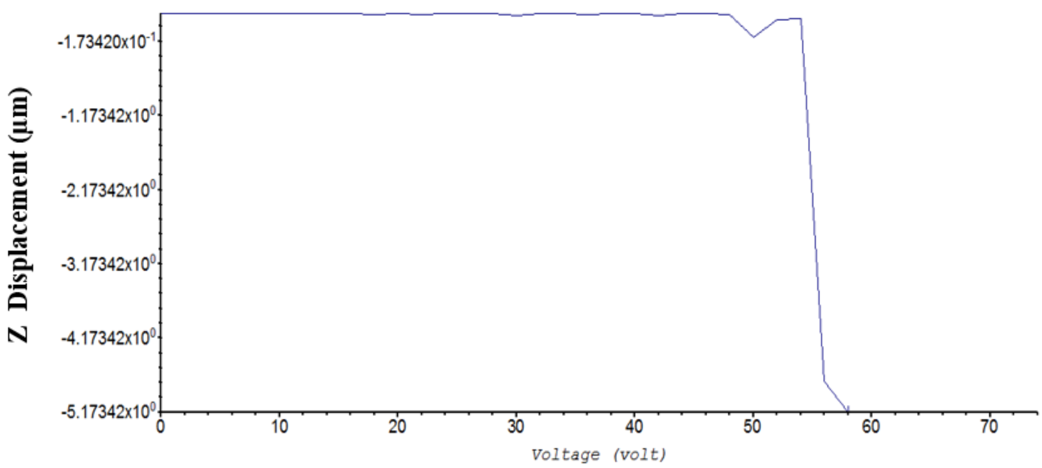

Fig. 6. Pull-in voltage value in our designed accelerometer (acceleration 1000g)

Table 4. Comparison of our designed accelerometer with previous ones

Print Year	Range of X Ax	Range of Axis	Range of Z A	s fF/g	Area (mm^2)
2007– [9]	+-1g	+-1g	+-1g	1.08	1.14
2006- [10]	0	0	+-5g	474	.92
2005-[11]	+-1g	+-1g	+-1g	6800	63
2009- [12]	+-5g	0	0	9500	33.2
1996-[13]	+-5g	0	0	1.2	0.42
2004- [14]	0	0	+-500g	1.1	1.21
2005-[15]	+-100g	+100g	0	2	1.51
2013-[16]	+-66g	0	+-30g	10	1.16
2016-[17]	+-71g	+-71g	+-231g	21.6	56.6
2020-[8]	+-1000g	+1000g	+-1000g	3	1.1
This Work	+-1000g	+1000g	+-1000g	5.57	1.1

directions. In addition, this scheme had a proper occupying level, which is an unprecedented achievement in designing 3-axis accelerometers. Our proposed structure also measured accelerations separately in all the directions of the three axes. The acceleration of each of these axes had a zero effect on the acceleration of the other two axes.

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