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Simulation and analysis of suspension based single axis mems capacitive accelerometer

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ABSTRACT

This paper reports a comparison of different types of springs used in MEMS based capacitive accelerometers. In this work MEMS based Single-axis accelerometers are designed using different Suspension systems. Analysis of the structure is done for resonant frequency of 2kHz. Analytical modeling of the different suspensions is presented for the specified frequency. Stress, displacement and capacitive analysis of the accelerometer is done. The sensitivity of the accelerometer with parallel beam suspension is 70nm/g, 50nm/g for folded beam suspension and 35nm/g for serpentine beam suspension. Hence parallel beam suspension has 0.7 times improved sensitivity than folded beam and 2 times better than serpentine suspension accelerometer. Whereas the stress obtained for folded beam is better than the other two. Hence Parallel beam suspension is preferred for higher sensitivity and accuracy whereas Folded beam suspension is preferred for greater structural stability By comparing these devices, it is concluded that a compromise on certain parameters is required in order meet the requirements. If there is higher displacement sensitivity then there is lower mechanical stability and vice versa. The simulations are carried out using COMSOL Multiphysics.

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1. INTRODUCTION

Micro Electro-Mechanical systems is known as MEMS. Other names associated with it include micro-systems technology (MST) and micro-machines. A broad range of micro fabrication designs, techniques, and mechanisms that involve the tiny realization of moving mechanical parts are together referred to as MEMS[1].

A moving system's acceleration is measured with accelerometers, which are electromechanical devices. Measurement of acceleration is essential for many applications. Applications requiring motion sensing, such as vibration detection, shock, tilt, etc., can also benefit from the usage of these inertial sensors.The MEMS accelerometer's resolution needs to be greatly increased for specific applications[2]. For the purpose of detecting a change in displacement in a single axis, numerous single-axis accelerometers have been created. Recent advancements in fields like robotics, transportation, and aircraft have expanded the potential applications for single-axis accelerometers[3]. Like a spring-mass-damper system, MEMS Capacitive Accelerometer operates in a similar manner. A suspended proof mass is moved when acceleration is applied. Capacitive comb fingers are arranged in such a way that the capacitance varies with the displacement of the proof mass. The acceleration is measured using the change in capacitance[4].

A high displacement of the proof mass with acceleration is required for a high change in capacitance. In single-axis accelerometer high displacement will occur only in Y-axis, and displacement in other axis will be less hence it is neglected, also increases cross-axis sensitivity in y-axis[5]. The system is intended to operate at a 2KHz frequency. The springs in a single axis accelerometer are made to be as rigid as possible in the cross-axis direction while being as flexible as possible in the sensing direction. The proof-mass shouldn't move much even when acceleration is applied in the cross-axis direction[6]. As a result, the system only exhibits a quantifiable displacement in one direction. The stiffness should, in a perfect world, be great enough to prevent motion even when acceleration is applied in the other two directions[7].

As a result, a high-resolution MEMS accelerometer is suggested for 1G, 10G, 50G, and 100G (1G = 9.8 m/s2) sensing[8]. All of the proposed accelerometers have a 100G maximum displacement limit.

2. RESEARCH METHOD

2.1 Working of Basic model

The fundamental mechanical component of a MEMS accelerometer is a proof mass attached to a dashpot and sustained by a spring. Figure 1 illustrates how the spring and dashpot are linked to the frame in turn. The proof mass is displaced from its rest position when an external force is applied, and certain electronic equipment can measure this displacement to determine the acceleration. Piezoelectric, piezoresistive, and capacitive accelerometers are the three main types of accelerometers based on the sensing principle[9].

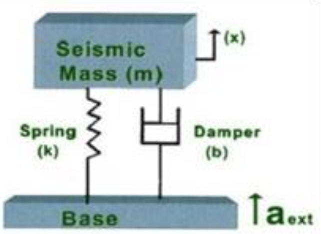

Figure 1: Basic Structure of mass spring dashpot

2.1.1 Proof Mass

A proof mass, also known as a test mass, is a known mass quantity that is employed as a standard in a measuring device while measuring an unknown quantity. The sensor component of the accelerometers is the micro-machined proof mass that is suspended between the two parallel plates which causes the spring in an accelerometer to bend.

2.1.2 Damper

Dampers are usually referred to as shock absorbers. In essence, a damper prevents a spring from moving. Any time a spring moves, it either gets squeezed or expanded, and hence there is constant movement in them.Hence the purpose of a damper is to minimise movement and any oscillations that result from it.

2.2 Working of MEMS capacitive accelerometer

A typical MEMS capacitive accelerometer is shown in the figure below. It can also be called a simple one-axis accelerometer.

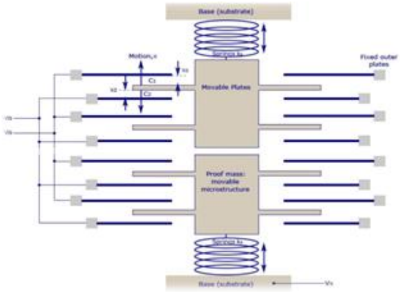

Figure 2: MEMS capacitive accelerometer

The capacitor plates are made up of the movable inner plates and the fixed outer plates. The proof mass travels in accordance with the applied acceleration, and the distance between the two plates changes as X1 and X2, turning out to be a function of the capacitance generated. A capacitance is created between the moveable and permanent outer plates as a result[10].

It is evident from the figure above that every sensor has numerous capacitor sets. The total capacitance of the lower capacitors is equal to C2, while the total capacitance of the upper capacitors is equal to C1. The excellent sensitivity and accuracy of the capacitive MEMS accelerometer are well known. The gadget merely relies on the capacitance value that arises due to the change in distance between the plates; it is independent of the base materials employed[11].

$$C_0 = \frac{\in A}{d} \tag{1}$$

Changes in the values of A or d can be used to determine changes in capacitance, which facilitates the operation of the MEMS transducer. The capacitance values mainly depend on the change of values of d or A as demonstrated in Figure 3 and 4. In Figure 3, distance between finger gap determines capacitance whereas in Figure 4, variation in capacitance is obtained by change in area of capacitive plate or the total overlap area.

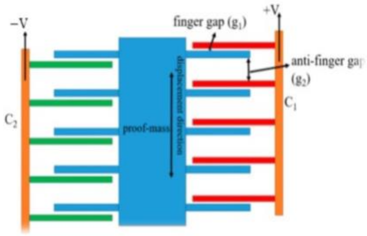

Figure 3: Variation of gap

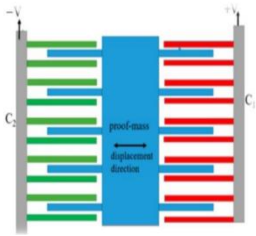

Figure 4: Variation of area

3. RESULTS AND DISCUSSIONS

A proof mass that has been damped on a spring is an accelerometer. The mass is shifted to the point where the spring may push or accelerate the mass at the same speed as the shell when the accelerometer senses an acceleration. The system is dampened so that the mass and spring's wiggles and oscillations won't interfere with the measurements that are required. Accelerometers always react differently to various acceleration frequencies due to damping[12]. When creating a capacitive based micro accelerometer, springs of various types can be used.

Three types of springs that are commonly used in micromechanical designs

a. The Parallel beam suspension

b. The Folded beam suspension

c. The serpentine beam suspension

The accelerometer performance is analyzed by designing the accelerometer with different suspensions. Values assumed for different parameters for designing the accelerometer structure are as given in the Table 1.

Table 1: Values considered for the design

Parameter	Value
Resonance frequency (f_r)	2kHz
Thickness of the suspension (d)	10μm
Depth of the proof-mass is (b)	10μm
Density of the of the of the proof mass is (ρ)	2330 Kg/m^3
Young's modulus (E)	150e9

3.1 The Parallel beam suspension

Parallel Beam suspensions are one of the least complex suspension systems used in MEMS devices shown in Figure 5. Accelerometers using Parallel- beam suspension tend to have higher sensitivity and moderate cross-axis sensitivity. Hence these beams are considered suitable for single-axis MEMS devices. The elastic coefficient is similar to other suspension system with slightly smaller cross coupling.

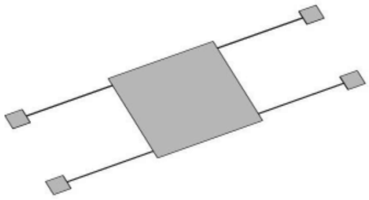

Figure 5: Parallel-Beam suspension

The steps to design the accelerometer with parallel beam is as shown below:

Step 1: To find the length of the suspension (L)

The spring constant along x-axis and y-axis respectively are:

$$k_x = \frac{4Ebd}{L} \tag{2}$$

$$k_y = \frac{4Ebd^3}{L^3} \tag{3}$$

On substituting the value of b, we get L = 1000μm.

The cross axis sensitivity is assumed as $\frac{k_x}{k_y} = 10{,}000$

From the equations 2 and 3, we get,

$$\frac{4Ebd}{L} \times \frac{L^3}{4Ebd^3} = \frac{L^2}{b^2} = 10{,}000$$

Step 2: To find the stiffness(k_y) : From equation 3,

$$k_y = \frac{4Ebd^3}{L^3} \quad , \tag{4}$$
$$k_y = 6N/m$$

$$k_y = \frac{4Ebd^3}{L^3}, \quad k_y = 6N/m \tag{5}$$

Step 3: To find the mass (m) of the proof mass.

The resonance frequency is given by

$$f_r = \frac{1}{2\pi} \times \sqrt{\frac{k_y}{m}} \tag{5}$$

The mass of the structure is found to be $= 37.99 \times 10^{-9}\ Kg$

Step 4: To find the length (s) of the proof mass

Density (ρ) = mass / volume (6)

Hence, mass = ρ × volume (7)

Also, $volume = s * s * d = s^2 \times d$ Substituting for volume in equation 6, we get mass = $\rho \times s^2 \times d$

Hence the length of the proof mass is found to be, s = 1276.8μ m

Step 5: To find the Force (F) required to displace the proof mass for an acceleration of 1g

Force F = mass x acceleration

where , 1g = 9.8 m/s²

So in equation 7, (8)

$F = 37.99\text{nm} \times 10^{-9} \times 9.8\ \text{m/s}^2$

Hence the force is found to be, F =372.302nN

Step 6: To find the displacement (x) when force (F) is applied

Force (F) = Ky × x

So, x = F / Ky (9)

Hence x = 62.05nN

4. CONCLUSION

4.1 Parallel Beam Suspension

The parallel beam accelerometer is simulated using COMSOL Multiphysics as shown in Figure 6. The stress at 100g is very high especially in region of the beam near the fixed anchor. The stress is about $2.5 \times 10^7\ \text{N/m}^2$ .There is very high possibility of the mass snapping apart if higher force is applied. Hence, the maximum limit of this model is restricted an acceleration of 100g. Since, this is comparative study the other models are also restricted to 100g. Figure 7 gives the simulation of displacement of the accelerometer.

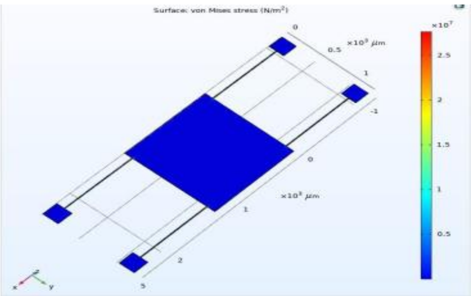

Figure 6: Stress Analysis of Parallel-Beam

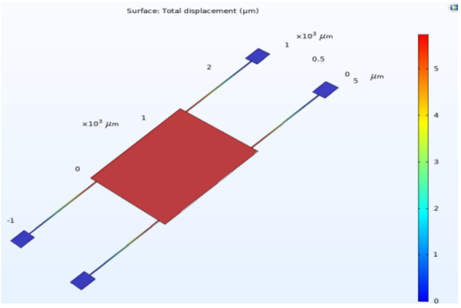

Figure 7: Displacement Analysis of Parallel-Beam

Since the device is limited to 100g, the distance of the gaps between the fingers of the comb can be calculated. Generally, the minimum gap between the fingers of the comb is 3 times the highest displacement of the proof mass designed for the device. The displacement of the proof mass at 100g is 7 micro meters. Hence, the minimum gap between the fingers is 20 micro meters. There are two gaps d1 and d2 between the fingers. The smaller one d1 has been found to be 20 micro meters, whereas the larger gap d2 is assumed to be 30 micro meters. Distance d1 and d2 repeat alternatively in the comb structure. The distance between the movable fingers and the proof mass is set at 25 micro meters.

4.2 The Folded beam suspension

These springs are beams which are folded once. They resemble the letter j hence are also known as j beams. Figure 8 shows the proposed accelerometer with folded beam type suspension. As the stiffness is inversely proportional to thickness of the beam and Proof mass displacement is inversely proportional to thickness of the beam, this type exhibits a Low resonance frequency compared to other springs of similar dimensions. Due to low resonance frequency, it has higher sensitivity and decreases total stress under external shock

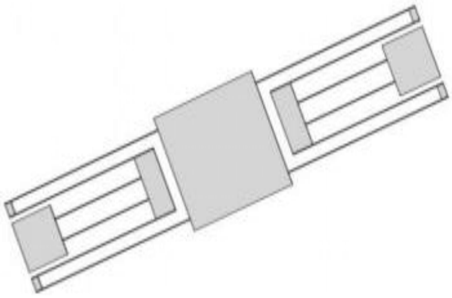

Figure 8: Folded-Beam suspension

From Figure 9, it is observed that the displacement along Y -Axis at 100g is 5µm. This indicates a uniform increase in displacement with respect to increase in acceleration. Hence the gap between the fingers and the proof-mass is 15 micro meters. The distance between the fingers is 5 micro meters.

Stress analysis is done on this accelerometer and it is seen that the stress along Y -Axis at 100g is (1.2×10^{7}) Pa shown in Figure 10. The stress here is significantly lower compared to Parallel beam Suspension. While there is lesser displacement compared to parallel, it is more structurally compact.

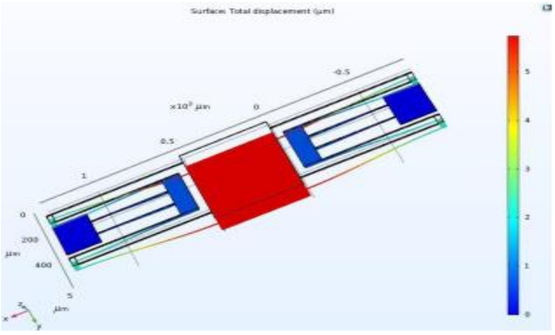

Figure 9: Displacement Analysis of Folded-Beam Accelerometer

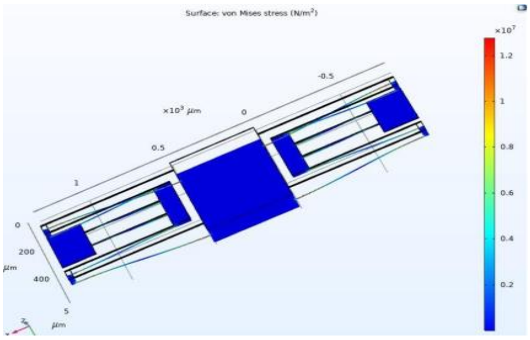

Figure 10: Stress Analysis of Folded-Beam Accelerometer

4.3 The serpentine beam suspension

Compact springs may have serpentine characteristics. This implies that small spring constant springs can be produced in a constrained space. Two serpentine beams are utilised in this suspension. The four corners of the proof mass are suspended by serpentine springs with uniform size in this serpentine flexure to maintain the proof mass's balance. The term "serpentine spring" refers to the spring's meandering beam, which resembles a snake. Of all the spring flexures, serpentine springs are the least rigid. The spring's meander dimensions can be altered to provide the necessary stiffness, which lessens the strain on the accelerometer's construction. Serpentine springs are highly sensitive to cross-axis motion. The proof mass displacement is higher compared to other spring suspensions. Serpentine springs are used to control deflection under high gravity accelerations. Figure 11 shows the accelerometer with serpentine beam suspension.

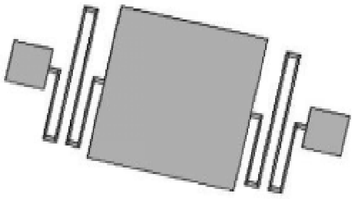

Figure 11: Serpentine-Beam suspension

The displacement at 100g is 3.5 µm as seen from Figure 12. Hence, the minimum distance between the gap is 10 micro meters. The smaller distance d1 is 10 micro meters and the larger distance d2 is set as 15 micro meters.

When the stress analysis is done along Y -Axis at 100g, it is observed that the accelerometer experiences a stress of (1.4×10^7)Pa shown in Figure 13. The stress measured here is lower compared to Parallel beam Suspension and it is slightly more compared to that measured in folded beam type accelerometer.

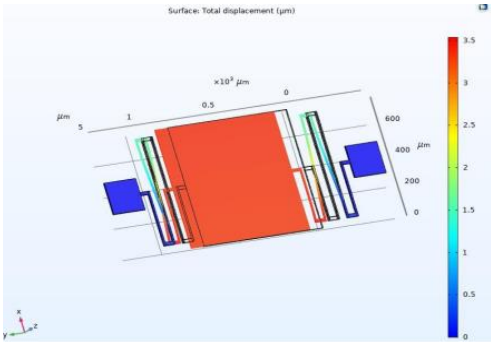

Figure 12: Displacement Analysis of Serpentine -Beam Accelerometer

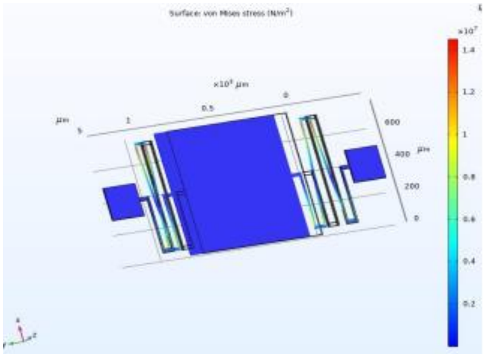

Figure 13: Stress Analysis of serpentine-Beam Accelerometer

4.4 Capacitive Analysis of Accelerometer

The capacitive analysis of the accelerometers for all the three types of suspensions are carried out using Electrostatic studies in COMSOL Multiphysics. The static capacitance of the structures are measured at 10g acceleration with and without including air block while simulating as shown in Figures 14 to 19.

4.4.1 Capacitive Analysis at 10g without Air block

when a force of 10g is applied to the proof-mass along Y-axis, the proof mass of Parallel beam accelerometer displaces 0.6µm from rest and produces capacitance of 1.47 pF, the proof mass of folded beam accelerometer displaces 0.5µm from rest and produces capacitance of 2.34 pF .while the serpentine beam based accelerometer displaces 0.35µm from rest and produces a capacitance of 1.99 pF as shown in Fig 14, 15 and 16 respectively.

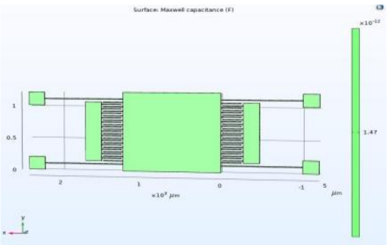

Figure 14: Parallel-Beam Capacitive Analysis at 10g

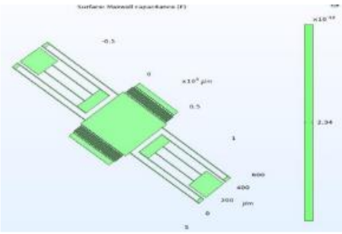

Figure 15: Folded-Beam Capacitive Analysis at 10g

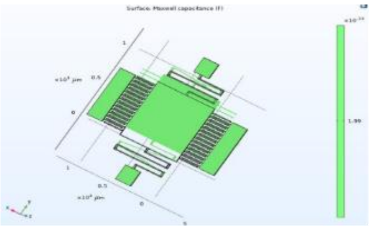

Figure 16: Serpentine-Beam Capacitive Analysis at 10g

4.4.2 Capacitive Analysis at 10g with Air-block

when a force of 10g is applied to the proof-mass along Y-axis which is placed inside an air block, the proof mass of Parallel beam accelerometer produces capacitance of 1.48 pF, the folded beam accelerometer produces capacitance of 2.15 pF .While the serpentine beam based accelerometer produces a capacitance of 1.99pF as shown in Fig 17,18 and 19 respectively.

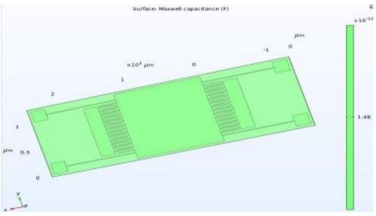

Figure 17: Parallel-Beam Capacitive Analysis at 10g with Air-block

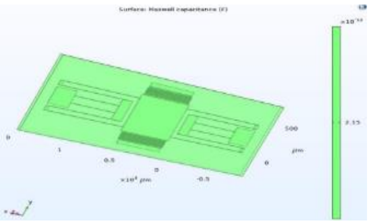

Figure 18: Folded-Beam Capacitive Analysis at 10 g with Air-block

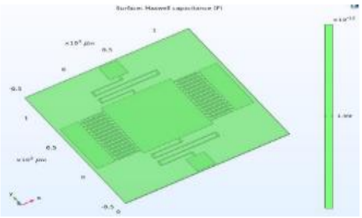

Figure 19: Serpentine-Beam Capacitive Analysis at 10 g with Air-block

The change in capacitance is higher in Folded beam for change in acceleration of 100g as tabulated in table 2 . The Serpentine Beam offers comparatively high change in capacitance for an applied force. From, analysing the above data it can be concluded that serpentine beam is sensitive to the lowest change in acceleration whereas the folded beam provides most precise reading of the acceleration. While parallel beam provides sufficient range of Capacitance and the displacement in parallel-beam is more in comparison with the other beams.

Table 2: Comparative Analysis at 100g

Beam	Force(N)	Displacement (μm)	Stress (N/m2)	ΔC(pF)
Parallel	3.70E-5	7	2.5E7	1.51
Folded	5.70E-6	5	1.2 E7	2.36
Serpentine	1.31E-5	3.5	1.4 E7	2.04

By Comparing the displacement and Stress in both the models, the following conclusions are drawn:

a. Parallel beam based accelerator has higher surface displacement along Y-axis compared to Folded beam and serpentine beam based Accelerometer and hence is more sensitive to applied Force.

b. Parallel beam based accelerator has lower surface displacement along X-axis compared to Folded beam and serpentine based Accelerometer and hence displays more cross axis sensitivity.

c. Parallel beam based accelerator has higher stress near fixed constraint compared to Folded beam and serpentine based Accelerometer and hence has lesser structural stability.

d. Parallel beam suspension is preferred for higher sensitivity and accuracy whereas Folded beam suspension is preferred for greater structural stability. Whereas serpentine suspension can be used for applications which require the characteristics of both parallel and folded beam suspensions.

This work is a comparative study of single-axis capacitive Accelerometer. Comparative studies over MEMS capacitive accelerometers are limited in number. This projects highlights the change in parameters of a single-axis accelerometer when different suspensions are used. Hence, this work can be continued in future for increasing the sensitivity and functionality of single-axis accelerometers for various requirements.

REFERENCES

[1] A Sthuthi; C.S Bhoomika, “Design, Modeling and Simulation of Micromechanical Suspension System for the Detection of Screech” 2021 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT), December 2021. DOI: 10.1109/CONECCT52877.2021.9622570

[2] Rajib Ul Alam Uzzal, Ion Stiharu, Waiz Ahmed, “Design and Analysis of MEMS based Accelerometer for Automatic Detection of Railway Wheel Flat”. World Academy of Science, Engineering and Technology, 2009.

[3] Zakriya Mohammed, Alabi Bojesomo, Waqas A. Gill, Ibrahim M. Elfadel Abe, Mahmoud Rasras. "A crab leg suspension based dual axis MEMS accelerometer with low cross axis sensitivity" , 2016 IEEE 59th International Midwest Symposium on Circuits and Systems (MWSCAS), 2016https://ieeexplore.ieee.org/abstract/document/7870040/

[4] Daisuke Yamane, Toshifumi Konishi, Teruaki Safu, Hiroshi Toshiyoshi, Masato Sone, Kazuya Masu, Katsuyuki Machida. "A design of spring constant arranged for MEMS accelerometer by multi-layer metal technology" , 2016 IEEE 11th Annual International Conference on Nano/Micro Engineered and Molecular Systems (NEMS), 2016https://ieeexplore.ieee.org/abstract/document/7758281/

[5] Karbari Sudha R., Kumari Uttara, Pasha Roshan C., Gowda Vikas K.. "Design and analysis of serpentine based MEMS accelerometer" , AIP Publishing, 2018A Robin J, Dennis, H. Khir, M. Abdurrahman A. Ahmed, “Modeling and Simulation of polysilicon piezoresistors in CMOS-MEMS resonator for Biomarker detection in exhaled breadth” 6th International Conference on Intelligent Systems. Modeling and Simulation, Washington DC, USA, 2015.https://ui.adsabs.harvard.edu/abs/2018AIPC.1966b0026R/abstract

[6] Sarvesh Sonkar, Prashant Kumar, Deepu Philip, Ajoy k Ghosh, “Simulation and Analysis of Spring Based Transverse Axis Sensing MEMS Capacitive Accelerometer,” 7th International Conference on Control, Decision and Information Technologies, Prague, Czech Republic2020.https://ieeexplore.ieee.org/abstract/document/9263904/

[7] Xingyin Xiong, Wang Zheng, Kunfeng Wang, Zhitian Li, Wuhao Yang, Xudong Zou “Sensitivity Enhancement Of Mems Resonant Accelerometers By Using Electrostatic Spring,” 2020 IEEE.https://ieeexplore.ieee.org/abstract/document/9257480/

[8] Ming-Hui Chang, Han-Pang Huang. "A Novel Offset Cancellation Based on ParasiticInsensitive Switched-Capacitor Sensing Circuit for the Out-of-Plane Single-Gimbaled Decoupled CMOS-MEMS Gyroscope" , Sensors, 2013https://www.mdpi.com/48524

[9] Y.W.Hsu, I..Y.Chen, H.T.Chine, S.Chen, S.T.Lin and L.P.Liao,“New capacitive low-g triaxial accelerometer with low cross-axis sensitivity”, Journal of Micromechanics and Micro engineering, vo1. 20, no. 5, pp. 1-10, 2010.[1] Y.W.Hsu, I..Y.Chen, H.T.Chine, S.Chen, S.T.Lin and L.P.Liao,“New capacitive low-g triaxial accelerometer with low cross-axis sensitivity”, Journal of Micromechanics and Micro engineering, vo1. 20, no. 5, pp. 1-10, 2010.

[10] Ming Hui Chang, Han Pang Huang, “Simulation and characterization of a CMOS-MEMS gyroscope with Parastic insensitive sensing”, ARSO pp. 1-6, 2008.https://ieeexplore.ieee.org/abstract/document/4653593/

[11] Veena. S , Newton Rai , H.L. Suresh , Veda Sandeep Nagaraja, “Design, Modelling, and Simulation analysis of a Single Axis MEMS-based Capacitive Accelerometer”,IJETT journal,2021.https://arxiv.org/abs/2111.03816

[12] b12https://link.springer.com/article/10.1007/s00542-018-04292-0