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Structural Designing and Simulation of Capacitive Accelerometer

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***Abstract** -This paper presents structural working principle and different characteristics of various types of accelerometer Capacitive accelerometers are one of the simplest structured and also widely used. They became crucial in automobile industry, aviation industry to measure tilt and shock. The basic principle of accelerometer follows Newton's second law which states that any object undergoing acceleration experiences force acting on it. We sense the motion using capacitance of the plates. In capacitive accelerometer the beam acts as a fixed metal plate while the mass a movable plate. When the mass moves the differential capacitance between plate changes. Depending upon the axes of operation, capacitive accelerometer is divided into three parts such as single axis, double axis or multiple axis. Further capacitive accelerator is also divided on the basis of their structures such as comb drive, cantilever structured, bridge type accelerometer.*

***Keywords**- MEMS accelerometer, capacitive, dual axis, 3-axis, bulk micro-machine, surface micro-machine, comb drive, cantilever, and multi beam structure*

I. INTRODUCTION

An accelerometer is an electromechanical device that measures acceleration forces. These forces may be static, as well as dynamic caused by moving or vibrating the accelerometer. MEMS sensors have gained the popularity in market because of small size, high sensitivity, durability, low cost, less required maintenance replacing conventional sensors. The accelerometer can be single axis, dual axis, multi axis accelerometer. They are widely used to measure acceleration, tilt, inertial forces, shock, and vibration. These devices have many applications area in variety of area like military, automobile industry, biomedical applications, avionics, safety-arming in missiles system, navigation and guidance system.

Firstly this paper described the principle of operation of capacitive accelerometer based on second order spring mass damping system (for constant applied force, change in position of mass gives the magnitude of acceleration). The movement of mass also gives the direction of acceleration along the different axes. The capacitive accelerometers are grouped on the basis of number of axes of its operation.(i.e., single axis, double axis or multiple axis). The capacitive accelerometer have different structures based on arrangement of capacitive plates such as comb drive, cantilever beam and bridge type.

A great challenge has been raised to form the substrate that can be folded instead of rigid one. The recent trend is to fabricate the sensors on bendable substrates and to develop a MEMS sensor that can withstand >20,000 g and wide temperature range (-120'C to 180'C). [1]

II. PRINCIPLE OF OPERATION

An accelerometer is a second order spring mass damping system as shown in following figure. The basic principle of operation of an accelerometer follows Newton's second law which states that any object undergoing acceleration experiences force acting on it. Fig. 1 shows a basic model of an accelerometer where proof mass (seismic mass) has a mass of M, suspension beams have an effective spring constant of K, with damping factor of B. Consistent with Newton's second law of motion (F = ma), as an acceleration is applied to the device, a force develops which displaces the mass.[2]

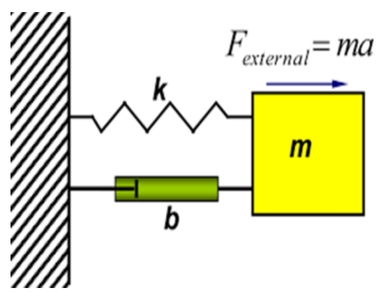

Fig no. 1 Basic operation

This acceleration can be sensed using different principle as change in capacitance, change in resistivity of material, piezoelectric etc.

In this paper we sense the motion using change in capacitance of plate. In capacitive accelerometer the beam acts as a fixed metal plate while the mass a movable plate. When the mass moves the differential capacitance between plate changes as shown in fig 2.

$$C_0 = \epsilon_0 \epsilon \frac{A}{d} = \epsilon_A \frac{1}{d}$$

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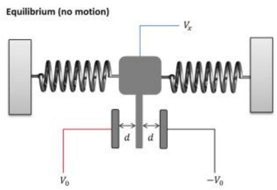
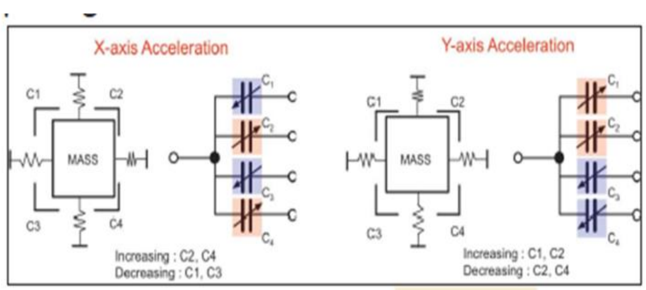


Fig no. 2 Differential capacitor

III. AXIS OF ACCELEROMETER

Accelerometer can be of single axis, double axis or multiple axis. Single axis MEMS capacitive accelerometers have found wide application in a various fields from consumer to space application. But currently researchers are trying on development of 2-axis and 3-axis accelerometers as a number of newly developed applications demand such accelerometers with moderate performance but at low cost. The axis of accelerometer depends on movement of proof mass. In a single axis accelerometer the sysmic mass moves only in one direction (eg. Single comb drive accelerometer).

Dual-axis accelerometers can be made by either using two single axis accelerometers or else by making a single chip design, which has advantage that it take less space and has less cost available on single chip. Recently Analog Devices have released their product; ADXL202, which is a dual axis MEMS accelerometer on a single chip. [3]



As the mass moves in X-direction the capacitor c2 and c4 increases while capacitor c1 and c3 decreases this change in capacitance sense by processing circuitry and as a result we get X-direction tilt result. Similarly as mass moves in Y direction the capacitance c1 and c2 increases while capacitor c2 and c4 decreases this change in capacitance sense by processing circuitry and as a result we get Y-direction Tilt result. Same principle used for detection of Z-direction tilt results in 3-axis accelerometer. There can be multiple axis accelerometer.

In three axis accelerometer the vertical and horizontal comb electrodes are designed to sense acceleration in X and Y axis respectively. However, the central Square shape electrode is embedded to detect acceleration in Z axis direction. Capacitance variation in X and Y directions is due to area changing between Fixed and movable electrodes but in Z axis is due to distance changing between them. As shown in Fig. 1 and 2 capacitance changing in 2 directions (X, Y) is differentially and is due to area changing among electrodes. This structure is free of cross axis sensitivity in all directions. The movable electrode fingers are smaller than their fixed counterparts which enable the device to detect 3-axis accelerations without any interface on each other. To the best of authors' knowledge, this is first time a 3-axis accelerometer is designed free of cross axis sensitivity.

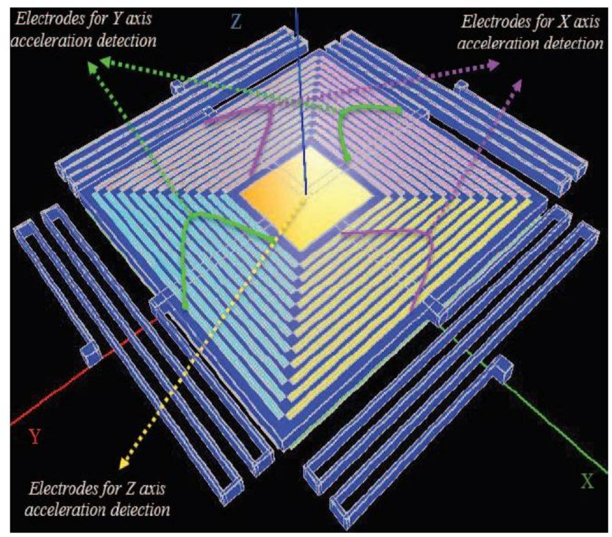


Fig. no.4 3D view of structure

To show eliminating cross axis sensitivity by new Configuration, the simple capacitance relation (C=kA/D), is used. As the structure measures acceleration in 3-axis, so the investigation should be done for all directions separately. Calculations for applied acceleration in X and Y axis electrodes due to similarity is the same, thus calculation is done for X axis. The capacitance variation is calculated in 3 conditions:

1. Applied acceleration is in plane (X or Y)

2. Applied acceleration is in out plane (Z)

3. Applied acceleration is in both out & in plane (Z&X or Z&Y)

4. Applied acceleration is in three directions(X&Y&Z)

Since for each of mentioned states the capacitive changing is detected by separated electrodes, then the electronic circuit can easily detects acceleration orientation.

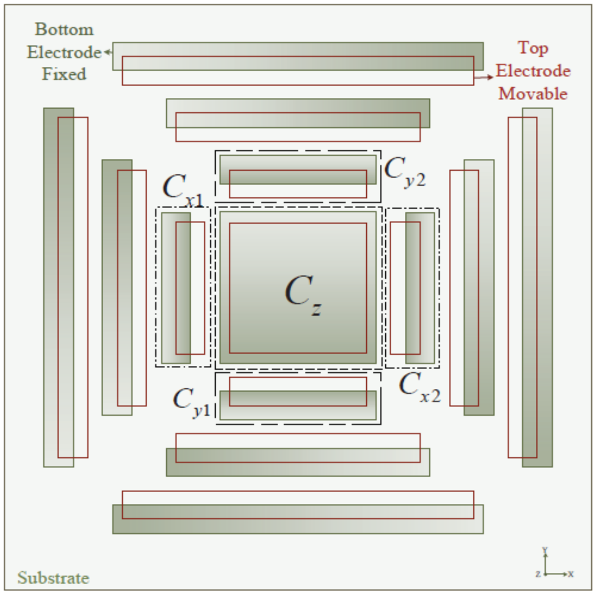


Fig.no.5 Arranged electrode (2D Top view)

IV. MICRO-MACHINING

A. Bulk Micromachining

B. Surface Micromachining

Bulk micromachining is a process used to produce micro machinery or micro electromechanical systems (MEMS). Unlike surface micromachining, which uses a succession of thin film deposition and selective etching, bulk micromachining defines structures by selectively etching inside a substrate. Whereas surface micromachining creates structures on top of a substrate, bulk micromachining produces structures inside a substrate.

Usually, silicon wafers are used as substrates for bulk micromachining, as they can be anisotropically wet etched, forming highly regular structures. Wet etching typically uses alkaline liquid solvents, such as potassium hydroxide (KOH) or tetramethylammonium hydroxide (TMAH) to dissolve silicon which has been left exposed by the photolithography masking step. These alkali solvents dissolve the silicon in a highly anisotropic way, with some crystallographic orientations dissolving up to 1000 times faster than others. Such an approach is often used with very specific crystallographic orientations in the raw silicon to produce V-shaped grooves. If the etch is carried out correctly the surface of the grove is smooth out perfectly, and the dimensions and angles can be precisely defined. Bulk micromachining technique usually used to create pressure sensor.

Bulk micromachining starts with a silicon wafer or other substrates which is selectively etched, using photolithography to transfer a pattern from a mask to the surface. Like surface micromachining, bulk micromachining can be performed with wet or dry etches, although the most common etch in silicon is the anisotropic wet etch. This etch takes advantage of the fact that silicon has a crystal structure, which means its atoms are all arranged periodically in lines and planes. Certain planes have weaker bonds and are more susceptible to etching. The etch results in pits that have angled walls, with the angle being a function of the crystal orientation of the substrate. This type of etching is inexpensive and is generally used in early, low-budget research. [4]

Fig no.6 (a) Bulk micro-machining

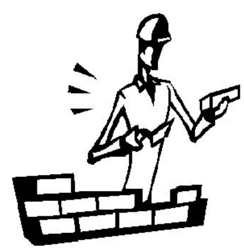


Fig no.6 (b) Surface micro-machining

V. MEMS CAPACITIVE ACCELEROMETER

I. COMB DRIVE ACCELEROMETER

Comb Drive accelerometer is surface micro-machined accelerometer. It's a one king of inertial mems accelerometer. In the comb like structure there are few electrodes are fixed and few are movable. In the shown figure, these two side electrodes are fixed.

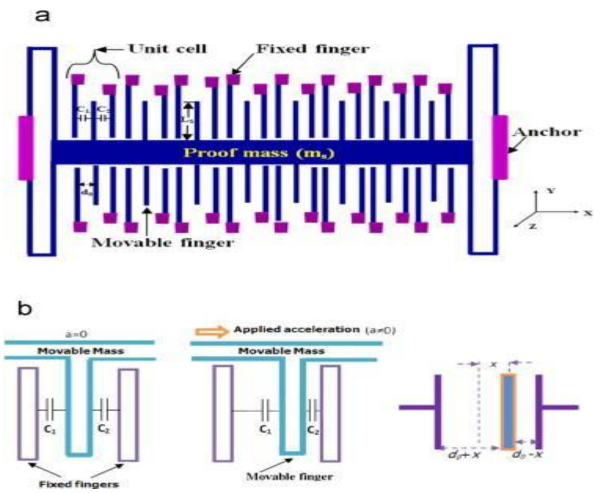


Fig no. 7 Comb Drive Accelerometer

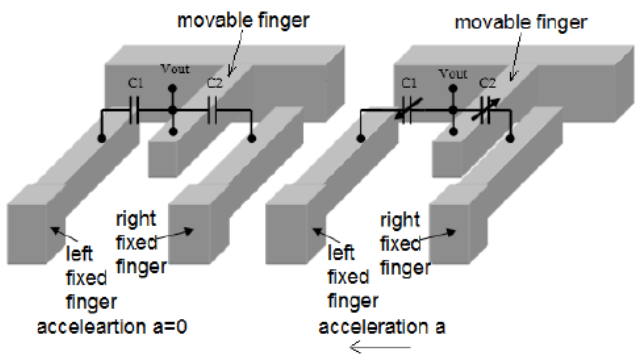


Fig no.8 Working Analogy [5]

At the peripherally, these electrodes are fixed with the help of anchor which are like screw. The movable electrode are also fixed by anchor but at only end point while fixed electrode fixed at every point. And if you whole structure is fixed but this can move. So with the acceleration, if you applied acceleration in this direction, so because of the mass of this structure, this will go down. So as a result of which the gap between the top electrode and the middle will increase and the bottom electrode and the middle electrode will decrease. So that means these are basically the two capacitances C1 and C2. One capacitance because of the increase of the gap will decrease and in the bottom capacitance, because of the decrease of the gap the capacitance will increase. So that means one is the capacitance will increase in other case capacitance will decrease the differential mode capacitance. So basically when there was no acceleration, the gap between the middle and the top and the gap between middle and the bottom will be the same. So as a result of which capacitance of both the top electrode and bottom electrode with the middle electrode will be the same. Now because of the acceleration movement of this structure, some capacitance will increase and some will decrease and with convenient circuit along with the sensor you can sense how much is the acceleration. So that is, this particular comb like structures is made using surface micromachining technology. And that has been fabricated by analog devices at the beginning and they are marketing this kind of the combed structure accelerometer which is based on change of capacitance with acceleration. Now this kind of accelerometer can work in the range of 2 to 500g, g is basically acceleration due to gravity. You can make the design so that it can measure along the three axis; the acceleration x axis, y axis and z axis. It has got lot of application in automobile sector, in industrial sector, consumer and military. And individually, the area wise, its applications in automotive within the airbag, alarms, ABS, door locking and brake lights; industrial application earthquake detection, gas shutoff, machine, health; consumer application navigation, computer peripherals, sport devices; military application navigation purpose, munitions and simulation.[6]

VI. CANTILEVER STRUCTURE ACCELEROMETER [7]

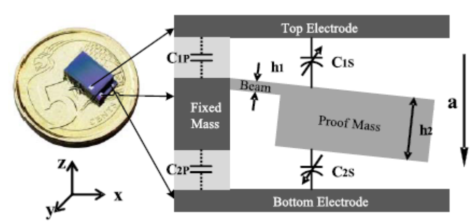


Fig no.9 Single Beam Cantilever

There are several type of mems accelerometer structure one of them is cantilever structure. In this type of structure the seismic mass held with cantilever.

$$z = \left(\frac{2ma}{Eb1h1^\wedge 3}\right)\{(15.1a1) - (5a1^2) - (12L^\wedge 2)\}a1$$

m= mass of proof mass

a= Acceleration

E= modulus of elasticity

b1= Width of beam

h1=Thickness of beam

L= Center of mass from the clamped end of beam

a1= Length of beam

z= defection force

In Cantilever structure, single flexure beam is used. The whole seismic mass is held with a single flexure beam. So the single flexure, its width is b1, its length of the flexure the cantilever is a1 which is shown in the diagram you can see here. So a1 is the length, b1 is width and h1 is the thickness of the beam. So a1, b1, h1 is known, m is the mass of the proof mass, there seismic mass in the center which is there and E is the modulus of elasticity. So as defined earlier modulus of elasticity and L is the center of mass from the clamped end of the beam, center of mass of the seismic structure; seismic mass structure from the clamped end of the beam. This is a clamped end of the beam from there say the center of mass if it is here, so then that is the length L. So if a is the acceleration then with acceleration a the seismic mass along z direction, if we accelerate the whole structure then the seismic mass will move, some displacement will take place and that displacement is z which is given by this relation. Now if we know the z movement, basically of the mass, then we can easily calculate how much change of the gap. Because top and bottom electrodes are fixed. So if we know the z, so in one case the gap between the two electrodes, that will be reduced by z; in other case the gap will be increased by z.

In this type of accelerometer the gap between plates is no constant therefore we cannot use differential parallel capacitance formula here. We have to integrate the length of bean also in our formula. Now C1 is the capacitance with the top electrode and seismic mass and C2 is capacitance with the bottom electrode and seismic mass. So now the C1 is equal to C2 is C0 when the mass is at rest that is obvious. So when this is there is no movement of the structure which is a rest position the C1 will be equal to C1.

$$C1 = \int_{a1}^{a2} \frac{\varepsilon b2}{d0 - A - B(x - a1)} dx$$

$$C2 = \int_{a1}^{a2} \frac{\varepsilon b2}{d0 + A + B(x - a1)} dx$$

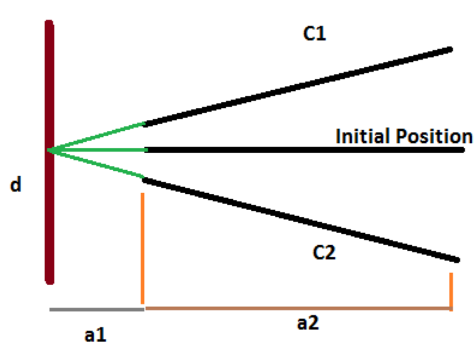


Fig no. 10 capacitance change [8]

Now with acceleration movement of the mass, that is basically like a fan, this will move up and down and between the fixed electrode and moveable electrode can be found out by integration along the length because the distance between two electrodes is not same all over length. Now the one point is very evident here that you see although we are telling parallel plate capacitance, the gap between top electrode and the middle is not same everywhere it varies. So that is why the capacitance is calculated by integrating from a1 to a2 where a1 is distance and a2 is from this point to this distance. So from a1 to a2 if we integrate this relation that will be the average value of the capacitance C1. Similarly C2 is also a1 to a2 and it is given by this expression. Now in this kind of structure there is a problem. The problem is the cross axis sensitivity[8] So now if this is the single flexure single cantilever structure, now if you make acceleration along y direction, say y direction is shown in the bottom in the diagram, z is the vertical and x, y in this plane of this table for example. So there if we move this whole structure along x direction, then the movement or the position of the seismic along z also. If you move along x axis, x acceleration, x direction, the rotation of the proof mass will be, this is the x along vertical. So there some movement will be there along z also. So that means this kind of structure will not give you that less cross axis sensitivity. Its value is very much linked to the mechanical structural design. Structural symmetry minimizes sensor cross-axis sensitivity.

For this reason we use multiple beam cantilever structure to decrease cross axis sensitivity of the structure [9][10].

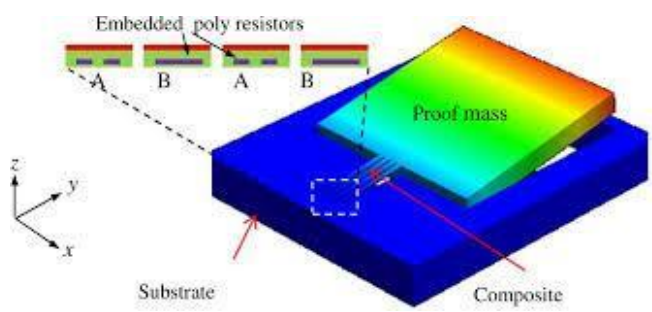


Fig no. 11 multiple cantilever structure

CONCLUSION:

MEMS industry in many areas is still a developing and new industry. In short time of span MEMS undoubtedly invade more and more consumer products. Frequency response and sense range are getting wider of MEMS sensor. Their sensitivity getting better and better every day. From studying various capacitive MEMS accelerometer we determine various advantage of them over piezoelectric and piezo resistive accelerometer. Our aim is to develop MEMS sensor that can measure high g up to 20,000 and have high temperature stability.

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