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Accelerometer: A Precise Way to Calibrate 'g'-force

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Abstract— This study is on a kind of device through which we sense the exact value of 'g' force acting on any object. This device is commonly called as Accelerometer. This study concludes the every type of it as well as its working, applications and merits & demerits. Moreover this review article throw a light on special kind of accelerometer i.e. MEMS Accelerometer.

Keywords— Accelerometer, MEMS, Piezo-electric, Piezo-resistive, Acceleration Sensor

I. INTRODUCTION

An accelerometer is an electro-mechanical device used to measure acceleration forces. Such forces may be static, like the continuous force of gravity or, as in the case with many mobile devices, dynamic to sense movement or vibrations. The Accelerometer's motion sensor can also be used to detect earthquakes, and may be used in medical devices such as bionic artificial body parts. Several devices, part of the quantified self-movement, use accelerometers. Acceleration is the measure of the change in velocity, or speed divided by time. Accelerometers allow users to understand the surrounding of an item better.

Accelerometers or acceleration sensors can be used to measure tilt, vibration or shock and to measure acceleration. Acceleration can also be called as first derivative of velocity and second derivative of displacement. The accelerometer is a mass spring system. There are different types of accelerometers and each type has its own characteristics, advantages and disadvantages which are unique to that category. [1]

II. TYPES OF ACCELEROMETER

A. Piezo-electric Accelerometer

Accelerometers behave as the transducers which produce an output signal proportional to the applied acceleration due to motion, vibration or shock. The output signal is an electrical signal. The accelerometers generate an electrical signal that is proportional to the force equivalent of the applied acceleration. Piezoelectric accelerometers are based on the self-generating piezoelectric effect of the piezoelectric materials. Piezoelectric accelerometers are typically made from quartz or a piezoelectric ceramic. The piezoelectric accelerometers that consist of built in signal conditioning circuitry are known as integrated circuit piezoelectric (ICP) accelerometers and those accelerometers that do not contain built signal conditioning circuitry are called high impedance accelerometers. We know that the accelerometer is a mass spring system. A conventional piezoelectric accelerometer consists of a small mass 'm', a spring which is made of piezoelectric material and a dashpot 'c' to provide adequate damping. The mass subjected to some acceleration places stress on the piezoelectric material, causing an output charge to appear between opposite ends of the piezoelectric material. When an input acceleration is applied, the whole system vibrates, which causes mass m to vibrate resulting in relative motion between the mass and the piezoelectric spring generating an electric charge proportional to applied acceleration. Since piezoelectric materials respond to changes in stress, these accelerometers cannot directly measure DC and very low frequency accelerations. Figure 1 shows a conventional view of this accelerometer & Figure 2 deflects schematics of the same.[2]

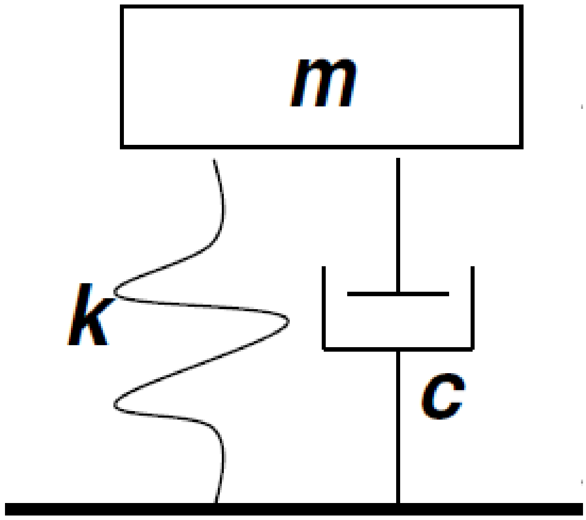

Fig.1. The Conventional Piezo-electric Accelerometer

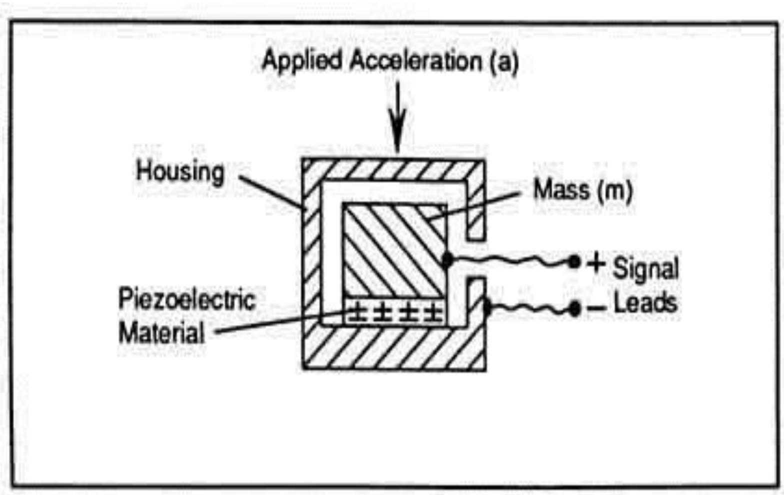

Fig.2. Schematics of Piezo-electric Accelerometer

B. Piezo-resistive Accelerometer

A piezoresistive accelerometer connects a piezoresistive material to a mass. When the mass deflects, this induces stress/strain on the piezo-resistor, and the resistive properties of the material change. Piezo-resistive accelerometers tend to have a simple interface. They can survive high shock conditions. They have medium frequency range (about 10 kHz). They can measure very low frequency accelerations. Unfortunately, there are some major disadvantages as well: Low sensitivity (10's of mV/g-~150mV/g). Tend to suffer from the effects of acceleration in perpendicular directions. Tend to have higher power consumption; typically a Wheatstone bridge is used at the front end. The resistance exhibits temperature dependence and limits high-temperature use. Figure 3 reflect a view of piezo-resistive accelerometer.[3]

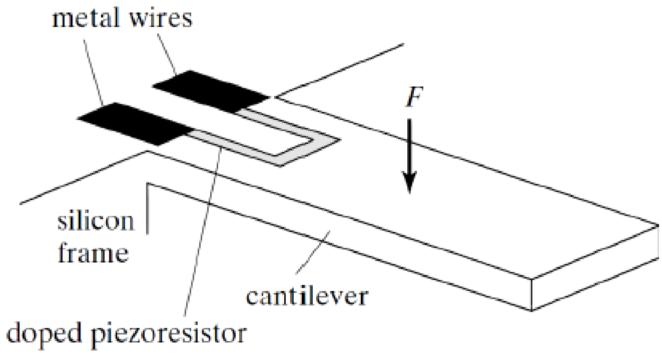

Fig.3. Piezo-resistive Accelerometer

C. Capacitive Accelerometer

Capacitive accelerometers are the most common types of MEMS accelerometers due to a high performance vs cost ratio. They also have minimal temperature dependence and a wide temperature range as the dielectric material is typically air. A capacitor consists of two parallel plates made of metal which is separated by a dielectric or an insulating material. The capacitance between two parallel plates is given by:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

Where, ε_0 indicates permittivity of free space and ε_r is the relative permittivity of the dielectric medium used, 'A' is the overlap area of the plates and 'd' is the separation between the plates. Any change in the overlap area, dielectric constant or the separation, causes the capacitance to change. The deflection or movement of one plate with respect to another (fixed) plate can cause the separation between them to change, which in turn changes the capacitance. This phenomenon is normally exploited in many capacitive type sensors. These work by making use of a miniature mass spring damper (2nd order) system. Capacitive accelerometers are a differential structure, providing one capacitor that increases and one that decreases for acceleration in the same direction.

The gap distance between the plates of the capacitors versus the input acceleration can be modelled with a mass spring damper system. A spring mass damper system can be represented through a second order linear equation. The damping force is proportional to the velocity and the spring force to the displacement. The equation can be obtained by a simple force balance equation as shown below. Also figure 4 below represents the schematics of capacitive accelerometer.[4]

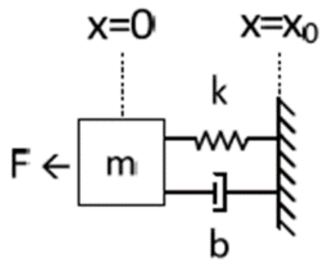

Fig.4. Schematics of Capacitive Accelerometer

$$F(t) = kx(t) + b\frac{dx(t)}{dt} + m\,\frac{d^2x(t)}{dt}$$

$$F(s) = kx(s) + bsx(s) + m\,s^2x(s)$$

$$x(s) = \frac{a}{s^2 + \frac{b}{m}s + \frac{k}{m}}$$

$$\omega_n = \sqrt{\frac{k}{m}}$$

Here ω_n is the resonant frequency of the system.

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

Above equation explains capacitance between two parallel plates without consideration of the fringing field. In reality, there are not only electric field lines normal to the plates, but also the field lines at the end of the plates, that have to be taken into account in calculating the capacitance. The fringing field effect results in increased capacitance between two parallel plates and also increases the difficulty in calculating the capacitance precisely.[3,4]

Depending on whether the change in area, distance or dielectric causes the change in capacitance, the capacitive type sensors can be divided into the following types:

a. Variable Area Type:

In this, the displacement of one plate by x causes the overlap area to decrease by ΔA. (as shown in Figure 5)

Where ΔA= w x, w is the width of the plates which causes the capacitance value to be

$$C = \frac{\varepsilon_r \varepsilon_0 (A - \Delta A)}{d}$$

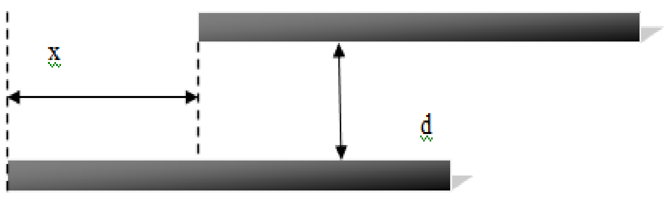

Fig.5. Variable Area Type

b. Variable Dielectric Type:

In variable dielectric type, the deflection or displacement changes the amount of dielectric material present between the plates. So, the total capacitance of the system now, is the sum of two capacitances, one with area A_1 and dielectric ε_1 and another with area A_2 and dielectric ε_2. (as shown in Figure 6)

$$C = \frac{\varepsilon_r \varepsilon_1 A_1}{d} + \frac{\varepsilon_r \varepsilon_2 A_2}{d}$$

$$A_1 = wx$$

$$A_2 = w(l - x)$$

where, w is the width of the plates.

Fig.6. Variable Dielectric Type

c. Variable Distance Type:

If the movement or deflection of plate causes the distance i.e. separation between the plates to increase by, then capacitance of the sensor is given by (as shown in Figure 7).

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d+x}$$

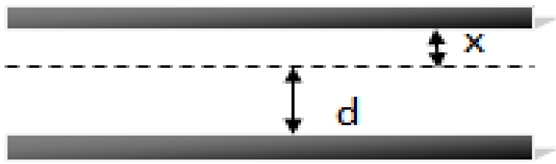

Fig.7. Variable Distance of seperation Type

This type of variable separation sensor can be non-linear. This problem of non-linearity is overcome by using three-plate differential displacement sensor. In this work, this type of three plate differential capacitive sensor is designed (as reflected by Figure 8)[5]

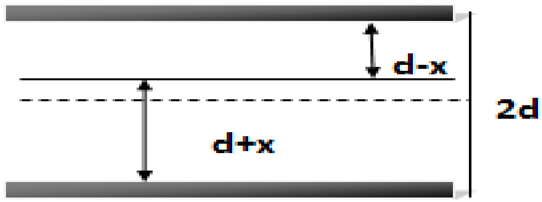

Fig.8. Differential Displacement Type

III.MEMS ACCELEROMETERS

A sensor can be successfully used depending on its performance, cost and reliability. However good the operational characteristics maybe but the success and marketability of the sensor mainly depends on its cost and size. Small sized sensor results in increase in applicability due to less weight, lower manufacturing cost as less materials are used and wide range of application. Cost is one of the critical factors. Even though, we reduce the size cost may not decrease much since cost of material processing is a very important factor. Use of silicon based microelectronics with micromachining technology can result in integration of micro sensors, micro actuators and signal conditioning circuitry on a single chip.[6]

MEMS (Micro Electro-Mechanical System) accelerometers are devices that measure the proper acceleration. In relativity theory, real acceleration is the physical acceleration experienced by an object. Sensing technologies make use of physical parameters from surrounding, like temperature, pressure, force and light. An accelerometer measures weight per unit of mass, a quantity also called as specific force, or g-force. Measuring g-forces allows users to for instance interact with products via gesture recognition.

MEMS capacitive micro accelerometers cross sectional diagram is shown in the figure. Here, the entire capacitive accelerometer is micro machined or formed from silicon and proof mass is sandwiched between metal plates.

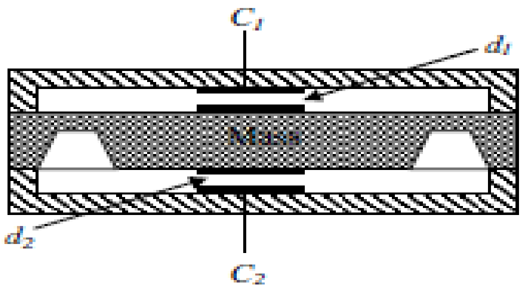

Fig.9. Capacitive Micro-Accelerometer

So, differential method can be applied as two capacitors are formed between the plates. Number of plates called fingers can be attached to the proof mass. Since the proof mass is movable these fingers are called movable fingers and the fingers of similar type attached to the rigid frame are called fixed fingers. The movable fingers and fixed fingers are arranged so that they from parallel capacitor.[7]

A 2D representation of capacitive micro-accelerometer is shown in Figure 9.

MEMS-based accelerometers are available in 1-, 2- and 3-axis configurations, with analog or digital output, in low-g or high-g sensing ranges.

Low g-force MEMS accelerometers:

- Output: analog and digital
- Number of axes: 1 - 3 axes
- Range of g-force: (+/-) 0 - 16 g

High g-force MEMS accelerometers:

- Output: analog and digital
- Number of axes: 1 - 2 axes
- Range of g-force: (+/-) 0 - 70 g

MEMS technology can primarily be used to realize two types of units: sensors and actuators. The sensors, usually in micro size, can be of many different types, e.g. for detection of physical phenomena such as vibration or any other kind of motion, sound, temperature, pressure etc. They have capability of transforming these physical phenomena to electrical signals. Pressure sensors, accelerometers and gyroscopes are typical examples of MEMS sensors.[8]

Due to their small size, low weight, low cost and low energy consumption, MEMS accelerometers have achieved great commercial success in recent decades. The figure given below identifies a MEMS accelerometer structure for human body dynamics measurements. As the primary structure, the capacitive accelerometer configuration was chosen such that, sensing part measures on all three axes, as it is a 3D accelerometer and sensitivity on each axis is equal. Silicon was used for L-shaped beams, copper for proof-mass. Hill climbing optimization was used to find the structure parameters. Proof-mass displacements were simulated for all the acceleration range in COMSOL Multiphysics.

IV. WORKING PRINCIPLE

MEMS accelerometers are available with different technologies. The most common are based on capacitors and gas chambers.

MEMS accelerometer with capacitors is typically a structure that uses two capacitors formed by a movable plate held between 2 fixed plates. Under zero net force the two capacitors are equal but a change in force will cause the movable plate to shift closer to anyone of the fixed plates, increasing the capacitance, and further away from the other fixed reducing that capacitance. This major difference in capacitance is detected and amplified to produce a voltage proportional to the acceleration.[9] The dimensions of structure are in the order of microns. Pictorial representation of its working is shown below as 10:

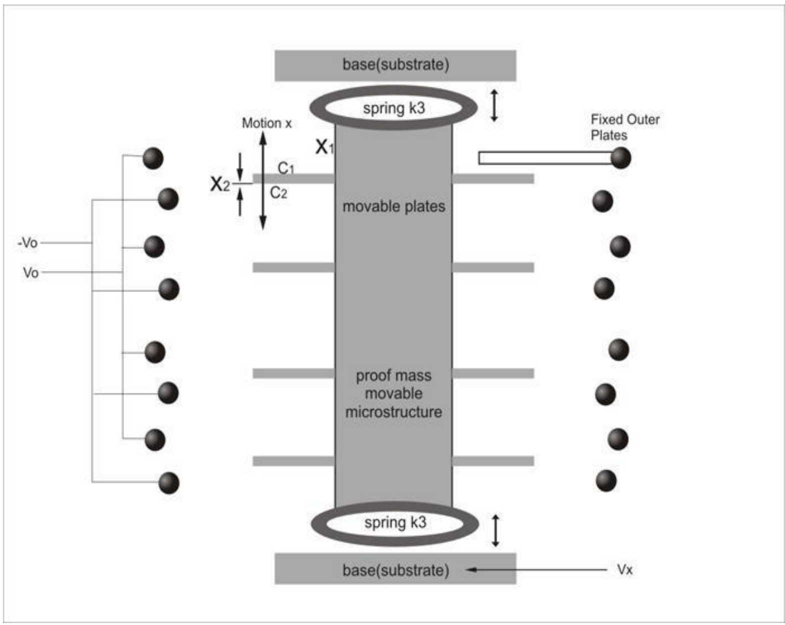

Fig.10. Working of Capacitive Accelerometer

The main component of MEMS based accelerometers with a capacitor is a cantilever beam with a proof mass (also known as seismic mass). Damping results from residual gas sealed in the device. As long as the Q-factor is not too low, damping doesn't reduce sensitivity. External accelerations make the proof mass deflect from its neutral position. This deflection is measured & marked in an analogue or digital manner. Most commonly, the capacitance between a set of fixed beams and a set of beams attached to the proof mass is calibrated & measured. This method is simple, reliable, and inexpensive.[10]

V. APPLICATIONS

The application of the Accelerometer extends to multiple disciplines, both academic and consumer-driven. For example,

- Accelerometers in laptops protect its hard-drives from damage. If the laptop were to suddenly drop while in use, the accelerometer would detect the instant free-fall and immediately turn off the hard drive to avoid hitting the reading heads into hard-drive platter. Without this, the 2 would strike and cause scratches to the platter for extensive file and reading damage.
- Likewise accelerometers are used in cars as the industry method way of detecting car crashes and deploying airbags almost suddenly.
- A dynamic accelerometer measures the gravitational pull to determine the angle at which device tilted with respect to Earth. By sensing the amount of acceleration, users analyze how the device is moving.

Smart phones and other mobile technologies identify their orientation through the use of an accelerometer, a small device of axis based motion sensing.

Accelerometers are normally classified based on their physical effect used in sensing mechanism. They are: piezoelectric accelerometers, piezo-resistive accelerometers and capacitive accelerometers. [11,12]

MEMS accelerometer is one of the simplest but also most applicable micro electro-mechanical device. They are widely used in low power, cost sensitive, motion and tilt-sensing applications like mobile devices, gaming systems, disk drive protection, image stabilization and health and sports devices. The best known applications are the Wii remote of Nintendo and Apple's iPhone.

There are numerous accelerometers available in the market. Out of these, MEMS accelerometers are projected to hold great promise for smart vibration sensing. For vibration based condition monitoring, MEMS accelerometers are expected to perform well. Accelerometers can be used to measure different types of signals such as: random, impulse and sinusoidal. MEMS technology can primarily be used to realize two types of units: sensors and actuators. The sensors, usually in micro size, can be of many different types, e.g. for detection of physical phenomena such as vibration or any other kind of motion, sound, temperature, pressure, etc. They have capability of transforming these physical phenomena to electrical signals.[9,10] Pressure sensors, accelerometers and gyroscopes are typical examples of MEMS sensors. MEMS accelerometers are also used in airbag deployment, Anti-Lock Braking Systems/Traction Control Systems, vehicle tilt monitoring, oil drilling, tilt measurement in harsh environments, seismic imaging and oil exploration, inertial navigation/GPS aid, smartphones/tablets/laptops, video game consoles, explosions/weapons tests, military surveillance, smart weapons, flight testing.[13,14]

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