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MEMS: THEORY AND USAGE IN INDUSTRIAL AND CONSUMER APPLICATIONS

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Abstract: MEMS is the integration of mechanical elements and electronics on a common substrate through specialized fabrication techniques. The capability of these devices to capture mechanical movements and provide a usable electronic output generates a whole new industry segment. The MEMS sensors family ranges from 2- and 3-axis linear accelerometers to single- and multi-axis gyroscopes, sensor modules, and microphones. This paper describes the theory of the operation of MEMS and its applications in industrial and consumer applications.

1. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. The electronics are fabricated using integrated circuit (IC) process sequences and the micromechanical components are fabricated using compatible micromachining processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

These techniques of integration are resulting into several types of MEMS – accelerometers, gyroscopes etc. MEMS is an enabling technology allowing the development of smart products, augmenting the computational ability of microelectronics with the perception and control capabilities of micro-sensors and micro-actuators and expanding the space of possible designs and applications.

Today, communication, consumer and industrial markets are considered emerging markets for MEMS devices and will be the key drivers for their success. In a mobile phone or PDA, for example, these sensors can add a new, intuitive motion-based approach to navigation within and between pages. In addition, game pads can use these sensors to enable the user to play by just moving the pad to allow the sensor to determine the inclination rather than pushing buttons. Another application uses a MEMS based accelerometer as a vibration detector in home appliances, i.e. for washers or dryers.

2. MEMS SENSORS

The MEMS defines the technology and not specific products. MEMS have become popular because of certain characteristics that these possess as given in Table 1 .

Table 1 : Silicon and Steel properties Comparison

	Steel	Silicon
Sensitivity to Stress	Low	High
Fabrication resolution (μm)	10	0.1
Fatigue failures	Yes	No
Mechanical Hysteresis	Yes	No

The silicon is almost as strong but lighter than steel, has large critical stress and no elasticity limit at room temperature as it is a perfect crystal ensuring that it will recover from large strain. Unfortunately it is brittle and this may pose problem in handling wafer, but it is rarely a source of failure for MEMS components. It is clear from the Table 1, that silicon is very good choice for sensors, thanks to no fatigue and its weight is also lesser compared to hard material like steel.

Several types of variations of MEMS are possible, depending on how the sensed motions is captured. The accelerometers and gyroscopes will be discussed in detail in the following sections.

2.1 Accelerometers

An accelerometer is an electromechanical device that will measure acceleration forces. These forces may be static, like the constant force of gravity pulling at your feet, or they could be dynamic - caused by moving or vibrating the accelerometer.

There are many different ways to make an accelerometer work. Some accelerometers use the

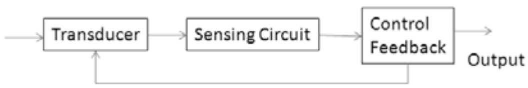

Figure 1 : Accelerometer sensing principle

piezoelectric effect - they contain microscopic crystal structures that get stressed by accelerative forces, which causes a voltage to be generated. Another way to do it is by sensing changes in capacitance. Two microstructures placed next to each other, have a certain capacitance between them. If an accelerative force moves one of the structures, then the capacitance will change. This change in capacitance can be converted to voltage variations that in turn results in an accelerometer. The sensitivity of the sense elements (the ratio of deflection to acceleration) is determined by the mass of the sense element, the distance from the center of mass to the torsion bar axis, and the torsion bar stiffness. Each complete sense element chip contains two wings for a total of four sensing capacitors.

Figure 1 depicts the general principle of accelerometer. The acceleration measurement is achieved by means of a proof- mass, spring and damper and damper system made up of micro-

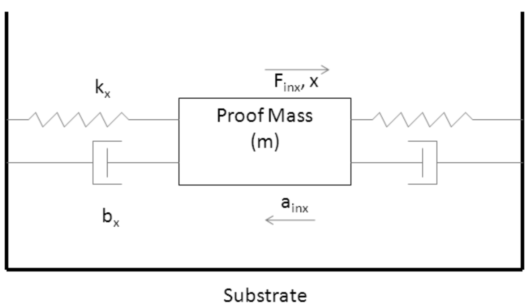

Figure 2 : Mechanical lumped parameter schematic of a single axis accelerometer

fabricated structures. The equivalent mechanical parameter schematic is shown in Figure 2. The substrate acceleration generates an inertial force on the proof mass. In the useful operating range of accelerometer, the differential equation in the sensing axis can be written as [1],[2],
(1)

$$F_{inx}(t) = m\frac{d^2x}{dt^2} + b_x\frac{dx}{dt} + k_x(t) = ma_{inx}(t)$$

Where 'Fin' is the feedback force, 'm' is the mass of the proof mass, 'x' is the deflection of the proof mass, 'b' is the damping coefficient and 'k' is the spring constant.

The device has suspended silicon structures along each direction which are attached to the substrate in anchor points and are free to move in the direction of the sensed acceleration. When acceleration is applied to the sensor, the associated moving elements displace from the nominal position, causing an imbalance in the capacitive half-bridge, which is measured using charge integration in response to a voltage pulse applied to the sense capacitor. Thus the motion measured by the sensor is translated into an analog or digital signal.

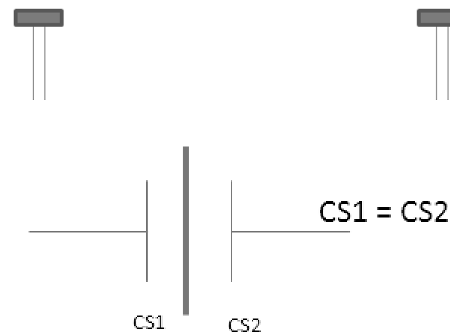

Figure 3 : Capacitive sensing of acceleration

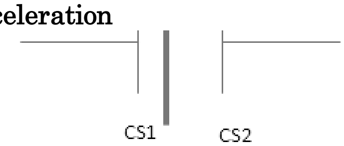

Figure 3 shows the principle of capacitive sensing of the element. The vertical frames have spring action and the springs are tied. In response to

the movement, the middle element moves in the direction opposite to the force applied due to inertia. This action causes the imbalance between the two capacitances as shown in Figure 4.

It can be shown [1] that in case of the differential capacitive sensing, the output voltage is linearly proportional to the displacement of the proof mass. This information is then processed to characterize the precise response of the accelerometer.

The discussion above has been about the simplest case of single axis accelerometer. However it is clear that the same discussion, in principle holds true 2-axis and 3-axis accelerometers [2] as well. The complexity of manufacturing or micro-machining varies with the addition of axes. A two axis accelerometer mechanical equivalent is shown in Figure 5.

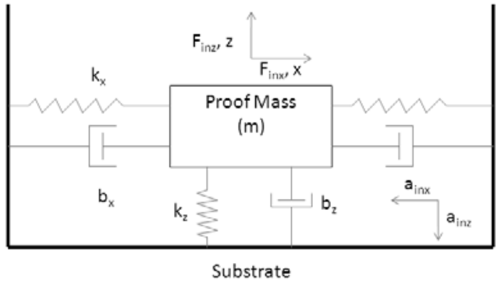

Figure 4 : 2-axis accelerometer lumped parameter model

Applications of the Accelerometers

The accelerometers find several applications. Vibration, free fall, shock, tilt, and rotation—all except rotation are actually different manifestations of acceleration in different situations. All of these motions can be detected by analyzing the acceleration value along the three MEMS axes. Acceleration sensed by the MEMS can be static or dynamic. Static acceleration describes slow motions and orientation in space where as dynamic signals are a consequence of vibratory/impact motions.

Accelerometers are widely used in machinery health monitoring of rotating equipments where the vibration data allows the user to monitor machines and detect the faults at an early stage so that preventive actions can be taken.

Vibration signals are high frequency periodic signals and can be thought of as acceleration and deceleration that happen within short interval of time. Digital MEMS implement a high pass filter in their signal processing chain that filter out the low frequency signals (also the DC component) so that only vibration motions are detected.

Tilt is a static measurement where gravity is the acceleration being measured. This functionality finds a tremendous use in construction and industrial inspection equipment, compensating for the position of a device for e.g., in electronic compass and GPS systems, image rotation in camera and PDA, electronic weighing scales, platform stabilization of industrial equipments, physiological monitoring of medical/diagnostic equipment.

A 3-axis MEMS accelerometer works as an inclinometer in static situations. The inclination angle can be obtained by calculating the angle between the sensor axis and the gravity force vector. Since in tilt measurements we use gravity as a reference, a full scale of 2g would suffice the requirements so that we get the maximum degree resolution. The tilt can be measured along MEMS X or MEMS Y axis. Let us analyze the situation in more detail.

Shock or impact causes impulsive force that registers as sharp spikes in the measured acceleration value. Unlike vibration, a shock is a non-periodic function that typically happens once.

A 3-axis accelerometer is capable of detecting a free fall motion. Free fall refers to a zero gravity condition in which the acceleration sensed by the MEMS along all the three axes is near to zero. In effect, we need to configure the free fall motion by adjusting the threshold and duration. Choice of threshold and duration should be made judiciously in order to avoid false free fall alarms. Free fall detection is commonly used for hard disks protection where the system detects a free fall and triggers the parking of the hard disk drive heads to prevent the damage and subsequent data loss. It also finds a potential use in mobile phones, where in an event of free fall the preventive actions are taken.

Already having occupied the consumer market in gaming, image stabilization in camcorders, PDA's, gesture recognition, MEMS due to their low cost, compact size and low power consumption are soon going to become ubiquitous in several applications in consumer, industrial, military and medical areas. With increased reliability there is almost no limit to what MEMS can be used for. There is a lot to say in the world of MEMS and a lot still needs to be explored!

2.2 Mems Gyroscopes

MEMS sensors are designed to measure angular rate using the Coriolis force. In the 1830's G.G. de Coriolis discovered that an object moving in a rotating frame would cause an observer on the rotating frame to see an apparent acceleration of the object. In other words, if an object is moving in a straight line, and it is subject to a rotation, you will see a deviation from the original straight line.

The Coriolis effect is an apparent deflection of moving objects when they are viewed from a rotating reference frame. The Coriolis force acts in a direction perpendicular to the rotation axis and to the velocity of the body in the rotating frame and is proportional to the object's speed in the rotating frame.

At a given rate of rotation of the observer, the magnitude of the Coriolis acceleration of the object is proportional to the velocity of the object and also to the sine of the angle between the direction of movement of the object and the axis of rotation[3]. The equation for the Coriolis force is

$$F_C = -2m\Omega \times v \quad (2)$$

Where
FC is the Coriolis Force, Ω is the angular velocity and v is the velocity.

2.3 Mems Microphones

MEMS microphones have recently emerged to compete with the traditional electret condenser microphones (ECM) [5]. Leveraging established high-volume silicon manufacturing processes, micro-machined acoustic devices meet price points set by electret microphones, while boasting superior reliability and robustness. Importantly, MEMS microphones can be made smaller than the most compact ECMs and are less susceptible to mechanical vibration, temperature variations and electromagnetic interference, which is important in cell phones and other devices with an audio input, such as notebook computers, video recorders, digital cameras, as well as hearing aids or electronic stethoscopes.

Addressing widespread user demand for a better audio experience in today's mobile devices, the new high-performance MEMS microphones enable dramatic advancements in sound quality and offer additional features such as noise suppression and directional voice pickup, useful to determine and filter out irrelevant noise. These features, which are valuable with the increasing use of cell phones in noisy and uncontrollable environments and can sensibly improve the quality of mobile conversations and conferencing, can be realized by incorporating multiple MEMS microphones in one device. Such microphone arrays improve noise cancellation and are now made possible with the unique packaging technology used for MEMS microphones.

2.4 Key Terms [5]

2.4.1 Sensitivity

An angular rate gyroscope is device that produces a positive-going digital output for counterclockwise rotation around the sensible axis considered. Sensitivity describes the gain of the sensor and can be determined by applying a defined angular velocity to it. This value changes very little over temperature and time.

2.4.2 Zero-rate level

Zero-rate level describes the actual output signal if there is no angular rate present. Zerorate level of precise MEMS sensors is, to some extent, a result of stress to the sensor and therefore zero-rate level can slightly change after mounting the sensor onto a printed circuit board or after exposing it to extensive mechanical stress. This value changes very little over temperature and time.

2.4.3 Self-test

Self-test allows to test the mechanical and electric part of the sensor, allowing the seismic mass to be moved by means of an electrostatic test-force. When the self test is activated by IC, an actuation force is applied to the sensor, emulating a definite Coriolis force. In this case the sensor output will exhibit an output change.

3. DEMONSTARTION OF MEMS FEATURES

In this section a few example demonstrations are described. These demos give an idea of the MEMS capability and their suitability for a variety of consumer and industrial application.

The inclination and vibration demos use the 8-bit microcontroller to analyze the input received from the MEMS and to represent the same visually on a pattern of LEDs and also to produce accompanying sounds. These are powered with standard AAA batteries. The demos are based on STM8S 8-bit microcontroller and LIS331, a nano three axes accelerometer from STMicroelectronics. The third application is based on the 32-bit microcontroller STM32 from STMicroelectronics.

3.1 Vibration Demo

The vibration demonstration board is a hand-held demonstration board which detects the vibration of the board and measures acceleration on all three axes (X, Y and Z) caused by this vibration. This information is displayed using the colored LEDs placed on three axes. The system can detect the tilt of the board and display this information using the bi-color LED at the center of the board. The system can also be configured to detect the circular motion of the board, in which LED patterns are generated depending on board movement.

Three modes of operation have been implemented. Each mode can be operated with or without the buzzer. An on board button takes the demo from one mode to the next in a cyclic manner.

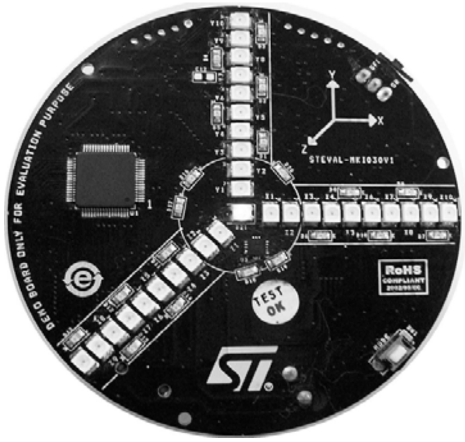

Figure 5 : Vibration Demo

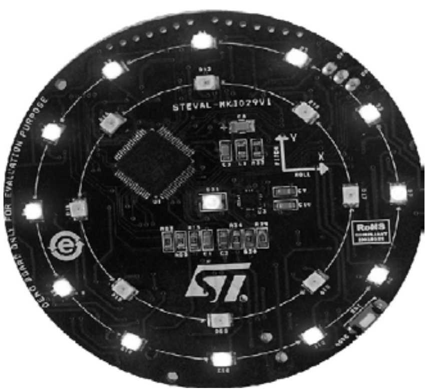

Figure 6 : Inclination Demo

The system automatically enters standby mode when there is no motion for more than 10 seconds and wakes up from standby when a vibration/motion is detected.

3.2Inclination Demo

The inclination demonstration board is a handheld demo which detects the tilt on X and Y axes of the board and provides a visual representation of this information using an array of colored LEDs placed in two circles. The demonstration can detect the free-fall of the board and displays the information for this event on the bicolor LED at the center of the board. The system can also be configured to detect the circular motion of the board, in which LED patterns are generated depending on board movement. The system automatically enters standby mode when there is no motion for more than 10 seconds and wakes up from standby when a vibration/motion is detected.

The key features of the demo are detection of the tilts on X- and Y- axes, free fall detection and the circular motion of the demo board.

3.2 Picture Rotation Demo

In another consumer application demo, an STM32 microcontroller is used to display the images on an on-board TFT. While the image is being displayed,

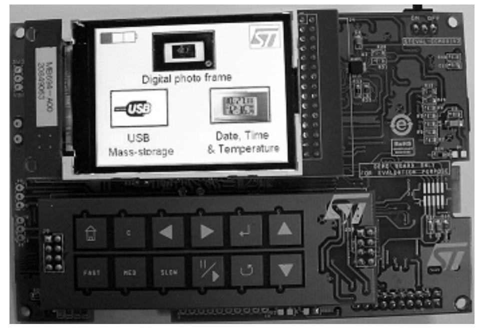

Figure 7 : Picture rotation demo

the user can change the orientation of the board or frame, the MEMS senses the same and the picture again stays vertical as before.

4. APPLICATIONS OF MEMS

In the above sections the basic principles of operation of accelerometers and gyroscopes have been discussed. Due to their small size and the reliability of operation, fast response and interface to the processing units like microcontrollers, a variety of industrial and consumer applications can be designed using these.

A photo frame where the MEMS sense the placement of the frame is a household application now. The same feature is being used in some of the high end mobile phones today.

MEMS find applications in the gaming industry in that these are able to capture the gestures also. In fact it is possible to build a toy vehicle that follows the path dictated by a human arm for its speed, turning left and right and moving in forward or reverse direction.

The applications of MEMS are increasing in several diverse areas beyond consumer and industrial. A digital compass can now be made using MEMS. In security applications, one can imagine a surveillance system being activated upon detection of any kind of movement at the chosen places. Healthcare is similarly another sector which is starting to use MEMS in a big way.

5. REFERENCES

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