Abstract—MEMS Sensors are devices used to obtain data from the physical surroundings and convert it into useful electrical signals for interpretation and analysis. Sensors can be classified depending on the physical properties that are measured. Any observable and measurable physical properties can be used as the measurand of a sensor. One of the physical properties that can be used for measurement is the acceleration of an object. This physical property can be measured using an accelerometer. The accelerometer measures the acceleration of an object by utilizing the classical Newtonian Law of Forces where forces of the same magnitude will be generated in the opposite direction of the applied force. This force is normally detected by a movable part in the accelerometer and is translated into electrical signal using various electrical principles for further processing and data extraction.

Index Terms—MEMS, physical properties, acceleration, accelerometer

I. INTRODUCTION

Acceleration is a physical property commonly seen in kinematic physics and is defined as the rate of change of velocity. The instantaneous acceleration can be evaluated by finding the gradient at the specific time in the velocity-time graph. This is illustrated in Figure 1.

From Figure 1, it can be seen that acceleration is a time domain physical properties. Hence, direct extraction of the acceleration of an object is not possible in standalone hardware circuitry without the help of a microprocessor for measuring time. Therefore, there is a need for an indirect approach for obtaining the acceleration of an object. There are many types of accelerometer used for measuring the acceleration of an object. They are classified depending on the methods of acquisition and electrical principles applied.

The early stage in the development of the accelerometer uses the piezoelectric properties of crystal as a mean for measuring acceleration. The piezoelectric crystal converts the force applied on the crystal due to acceleration into electrical signals. The amplitude of the signal is dependent on the direction and magnitude of the acceleration. However, MEMS technology is still in the developing phase and hence the piezoelectric accelerometer fabricated is bulky and not reliable. The application of the accelerometer is limited.

It is not until in the year of 1990 that accelerometers are commercialized and widely used in the automobile industries for triggering air-bag system in convertibles. As MEMS technology improved over the years, different types of mechanical structures can be fabricated in the microscale, which causes the popularization of the accelerometer. Advancement in the fabrication techniques further enhances the reliability and variety of accelerometer while constantly scaling down the device sizes.

In some applications, the accelerometer is integrated together with the gyroscope to form an inertial measurement unit (IMU). The IMU, together with a compass module and global positioning system (GPS) module are used by the military for precise motion detection and movement tracking. Although the original design of the accelerometer is used for measuring the acceleration of an object, modern application of the MEMS sensors also includes the measurement of vibration, shock, tilting angle and etc.
II. ACCELEROMETER SPECIFICATIONS

The accelerometer is measured in g where g is referred to the acceleration due to gravity or equivalent to 9.81 m s$^{-2}$. Some examples of the g force experienced in daily life are as shown in Figure 2.

<table>
<thead>
<tr>
<th>Description</th>
<th>“g” level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth’s gravity</td>
<td>1g</td>
</tr>
<tr>
<td>Passenger car in corner</td>
<td>2g</td>
</tr>
<tr>
<td>Bumps in road</td>
<td>2g</td>
</tr>
<tr>
<td>Indy car driver in corner</td>
<td>3g</td>
</tr>
<tr>
<td>Bobsled rider in corner</td>
<td>5g</td>
</tr>
<tr>
<td>Human unconsciousness</td>
<td>7g</td>
</tr>
<tr>
<td>Space shuttle</td>
<td>10g</td>
</tr>
</tbody>
</table>

Figure 2: g Force Experienced by Human [3]

Although in general, there is still no standardized specification for describing the performance of an accelerometer, there are some accelerometer terminologies that are used in the industries. These terminologies are used for describing the specification of an accelerometer and are shown in Figure 3.

Figure 3: Accelerometer Terminology [3]

Figure 3 shows the definition of +1g, 0g and -1g used by manufacturers such as Silicon Designs Inc., Texas Instrument and Analog Devices. These definitions are used for describing the specification of the accelerometer.

Some of the specifications commonly found are as shown:

a) Linearity
The linearity of a sensor describes the proportionality of the relationship between the input signal and the output signal. Ideally, the output signal of the accelerometer should fit the straight line equation. The linearity can also be defined as the deviation of the output signal from the ideal condition and can be calculated using the following equation

$$\text{Linearity} = V_{out,0g} - \frac{1}{2}(V_{out,+1g} + V_{out,-1g})$$

Where $V_{out,0g}$ is the output voltage at 0g, $V_{out,+1g}$ is the output voltage at +1g, $V_{out,-1g}$ is the output voltage at -1g

b) Sensitivity
The sensitivity of an accelerometer shows the change in the output voltage per 1g unit of acceleration and is measured in mV/g.

$$\text{Sensitivity} = \frac{\Delta V_{out}}{\Delta g} = \frac{V_{out,+1g} - V_{out,-1g}}{2g}$$

The linearity and sensitivity can be illustrated as shown in Figure 4.

Figure 4: Sensitivity and Linearity of Accelerometer [3]

c) Cross Axis Sensitivity
An accelerometer can measure the acceleration for three different axes, namely x-axis, y-axis and z-axis. Ideally, the acceleration in one axis is independent of the other axis. However, this is not the case in practical application. The cross axis sensitivity measures the output voltage caused by other axis of measurement and is often expressed in percentage of accelerometer dynamic range.

d) Dynamic Range
The dynamic range of an accelerometer is the total input range of the sensor within the sensor’s functional limit. It is often measured in g.

e) Ratiometric
Ratiometric measures the influence of the supply voltage on the output voltage. A change in the supply voltage would cause variation in the output voltage. It is often measured in percentage with respect to supply voltage.
f) Noise
The noise in an accelerometer is originated from the 1/f noise or flicker noise. As frequency of the accelerometer increases, the noise decreases. Hence, for low frequency application, it is crucial for selecting accelerometer with low noise. Noise is measured in $\mu g/\sqrt{Hz}$.

g) Frequency Response
The frequency response of an accelerometer shows the bandwidth of the accelerometer where the output voltage is linear and stable. It is measured in Hz.

A sample accelerometer datasheet obtained from Silicon Designs Inc. is as shown in Figure 5. The operating voltage and current is also included for proper usage of the accelerometer. Mass is also provided which acts as a guidance for selecting the suitable accelerometer. As a rule of thumb, the object of interest where its acceleration is to be determined should have at least a mass of tenth order higher than the mass of the accelerometer for more accurate result [ref].

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MIN</th>
<th><em>TYP</em></th>
<th>MAX</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Axis Sensitivity</td>
<td>2</td>
<td>3</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Bias Calibration Error $^2$</td>
<td>-0.02</td>
<td>2</td>
<td>4</td>
<td>% of $F_{full}$</td>
</tr>
<tr>
<td>Bias Temperature Shift</td>
<td>-0.05 thru -200</td>
<td>1</td>
<td>2</td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Scale Factor Temperature Shift $^2$</td>
<td>-0.05 thru -200</td>
<td>100</td>
<td>300</td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Scale Factor Calibration Error $^2$</td>
<td>1</td>
<td>2</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Non-Linearity</td>
<td>-0.02 thru -100</td>
<td>0.5</td>
<td>1.0</td>
<td>% of span</td>
</tr>
<tr>
<td>Power Supply Rejection Ratio</td>
<td>40</td>
<td>dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>4.5</td>
<td>5.0</td>
<td>5.5</td>
<td>V</td>
</tr>
<tr>
<td>Operating Current $^2$</td>
<td>2</td>
<td>3</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>Clock Input Voltage Range</td>
<td>-0.5</td>
<td>$V_{supply}$ to 0.5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Notes (not reading code)</td>
<td>6</td>
<td>grams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable Mass</td>
<td>25</td>
<td>grams/meter</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Datasheet of an Accelerometer [16]

III. TYPES OF ACCELEROMETER

There are different types of accelerometer exists in the market, which are applied in many fields. Although there are many variety of accelerometer, at functional level, they have the same measurands, which are acceleration, vibration and shock. The only difference between the various accelerometers is the underlying principles and operations used.

Generally, the following are some types of accelerometer that can be found in the market:

i. Capacitive
ii. Piezoelectric
iii. Piezoresistive
iv. Hall Effect
v. Magnetoresistive
vi. Heat Transfer
vii. Optical
viii. Tunneling

A. Capacitive

The capacitive accelerometer uses the change in capacitance of a capacitor as a mean for measuring the acceleration of an object. The general structure of a capacitive accelerometer consists of a moveable central proof mass which provides the inertia necessary for providing the acceleration force for measurement, a fixed capacitive electrode to form a capacitor with the moveable proof mass, an anchor for providing support to the proof mass and a spring to provide the flexure of the proof mass.

The change in acceleration is translated as the change in capacitance which can then be processed by microelectronics circuit. There are three methods for detecting the change in capacitance. The first method uses the parallel plate capacitor. When using that parallel plate capacitor, it is assumed there is no fringe capacitance and that the distribution of magnetic field between the capacitor plates is even. The change in the distance between the plates would cause changes in the capacitance.

The second method uses the fringing effect of a capacitor to detect the change in capacitance. As MEMS accelerometer scales down, the effect of fringing is no longer negligible and hence can be used as measuring parameter. Last but not least, the interdigitated capacitor accommodates both the effect of a parallel plate capacitor and fringing capacitor. Therefore, it is the preferred structure for implementing the capacitive accelerometer. The different types of capacitor are as shown in Figure 6.

Figure 6: Different Types of Capacitor [15]

However, the capacitor form using MEMS technology has very small capacitance value due to small area and distance which requires complex and expensive conditioning circuit. This is overcome by using multiple fingers in the design of the accelerometer. The interdigitated fingers are connected in parallel which provide a larger resultant capacitance. The design of an interdigitated capacitive accelerometer using thin film technology is as shown in Figure 7.
B. Piezoelectric

The piezoelectric accelerometer utilizes the piezoelectric properties of a crystal for detection and measurement of acceleration. The piezoelectric material produces voltage when force is applied to it for both compression and stretching. The output voltage is then passed through conditioning circuit for obtaining the acceleration. There are three modes in piezoelectric accelerometer: sheer mode, compression mode and flexural mode.

i. Sheer Mode

In sheer mode, the force applied to the piezoelectric material consists of only sheer force and not compression. The sheer force due to acceleration is detected by the piezoelectric material and is converted into useful output voltage. The conditioning circuit is integrated into the piezoelectric sensor known as integrated circuit piezoelectric (ICP). The structure of a sheer mode piezoelectric accelerometer is as shown in Figure 8.

Figure 8: Sheer Mode Piezoelectric Sensor [17]

The piezoelectric material is situated between the center post which is connected to the base and a seismic mass. The preload ring is used to attach the seismic mass and the piezoelectric material to center post. The base of the accelerometer would then be mounted on the object of interest. Any forces experienced by the base is transferred to the piezoelectric material as a sheer force and converted to voltage. The acoustic shield is used to reduce the cross axis sensitivity from the horizontal axis as the main axis of the sensor is in the vertical axis.

ii. Flexural Mode

In flexural mode, the piezoelectric material is supported on a fulcrum and would experience strain on the piezoelectric material as force is applied to the accelerometer. The seismic mass acts as a balance for the piezoelectric material to balance on the fulcrum. Since force exerted on the piezoelectric material only focuses on the center part of the piezoelectric material which is governed by the area of contact between the piezoelectric material and the fulcrum, the flexural mode piezoelectric sensor is insensitive to horizontal motion. The structure of flexural mode piezoelectric accelerometer is as shown in Figure 9.

Figure 9: Flexural Mode Piezoelectric Accelerometer [17]

iii. Compression Mode

In compression mode piezoelectric accelerometer, the acceleration of an object is detected as compression force exerted on the piezoelectric material. The structure of the accelerometer is as shown in Figure 10.

Figure 10: Compression Mode Piezoelectric Accelerometer [17]

The piezoelectric material is situated between the seismic mass and the base. It is then secured using a pre-load stud. When the base experience forces, it is translated as a compression to the piezoelectric material which then produces electrical output. There are two different types of compression mode piezoelectric accelerometer, which is single ended compression accelerometer and isolated compression accelerometer.

The single ended compression accelerometer has its piezoelectric material mounted on the base of the accelerometer. This might cause the piezoelectric material to experience base strain which will affect the accuracy of the output voltage produced. The isolated compression accelerometer however has a washer between the piezoelectric material and base to reduce the effect of base strain.
A. Piezoresistive

The piezoresistive accelerometer also utilizes the piezoelectric properties. Each material has this property, which is governed by the gauge factor. The resistance of a material would change as it is stretched and compressed due to Poisson effect. The structure of the piezoresistive accelerometer is as shown in Figure 11.

![Figure 11: Piezoresistive Accelerometer [1]](image)

The coloured portion in Figure 11 is used to measure the resistance at the specific point. Each of the points can be regarded as an individual resistor, which is arranged in a Wheatstone bridge configuration to provide the output voltage.

B. Hall Effect

As the name suggests, the Hall Effect uses the principle of electromagnetism as its main mechanism. In Hall Effect accelerometer, two coils are placed in parallel opposite to each other. One of the coils is supplied with voltage which causes electromagnetism. The other coil is used as the sensing element for detecting changes in magnetic field. When the accelerometer experiences acceleration, the coil with external supply would vibrate. This causes the magnetic field to fluctuate and cuts through the second coil. As in Faraday’s law of electromagnetic induction, the movement of the magnetic field across the second coil causes induced current. This current is then processed to obtain the acceleration of the object. The structure of the Hall effect accelerometer is as shown in Figure 12.

![Figure 12: Hall Effect Accelerometer [1]](image)

C. Magnetoresistive

The magnetoresistive accelerometer has the same setup as in Hall Effect accelerometer. However, the parameter measured in magnetoresistive accelerometer is the impedance in the coil due to fluctuation of the magnetic field. The impedance can be obtained using the Wheatstone bridge configuration and is measured from the null offset.

D. Heat Transfer

Another physical quantity that can be used for calculating the acceleration is the rate of heat transfer. In thermodynamics, when a system is in equilibrium and stable, the rate of flow of heat between two objects is constant. The net flow of heat is zero. When the equilibrium state is disrupted, heat would flow from region with greater heat energy to region with lower heat energy. This is utilized in heat transfer accelerometer. In heat transfer accelerometer, a single heat source point is suspended at the center of a cavity. Thermoresistors are then placed around in the accelerometer to detect the change in temperature gradient. When the accelerometer experiences acceleration, the heat point source would change in location causing net flow of heat. This then detected by the thermoresistor which produces output voltage. The structure of the heat transfer accelerometer is as shown in Figure 13.

![Figure 13: Heat Transfer Accelerometer [1]](image)

E. Optical

The optical accelerometer uses the same basic concepts as the heat transfer accelerometer, with light as its source instead of heat. A light source, usually LED emits light to an array of photodiodes. The photodiodes convert the light energy into electrical energy, depending on the light intensity of the LED. The light intensity detected by the photodiodes is controlled by a shutter. In neutral position, the photodiodes are shielded from the light source by the shutter. However, when acceleration is applied, the shutter would offset from its neutral position, causing more light to pass through the shutter and reaches the photodiodes. The structure of the optical accelerometer is as shown in Figure 14.

![Figure 14: Optical Accelerometer [1]](image)
F. Tunneling

Tunneling is a concept introduced in quantum mechanics. In traditional mechanics, an electron will not be able to pass through a potential barrier due to insufficient energy. However, in Heisenberg uncertainty principle, a minute amount of electrons would have sufficient energy to break through the potential barrier. This concept is used in the tunneling accelerometer. In tunneling accelerometer, the distance between a tunneling tip and the seismic mass is maintained by the deflection electrode using a feedback loop. The distance required for tunneling to occur is in the order of Armstrong and the force required for maintaining this distance using a feedback loop is used to evaluate the acceleration of the system. The structure of the tunneling accelerometer is as shown in Figure 15.

IV. MODELING OF AN ACCELEROMETER

 Occasionally, the modeling of the accelerometer is required when designing the geometry of the accelerometer. Since MEMS accelerometer involved in both mechanical and electrical components, the modeling of the accelerometer should also consists of both the electrical and mechanical analysis.

Consider the mechanical components of an accelerometer in a single axis. The accelerometer generally consists of a movable seismic mass which converts acceleration into displacement. This can be modeled as a mass, spring and damper as shown in Figure 16.

\[
G(s) = \frac{1}{Ms^2 + f_\nu s + K}
\]

with natural angular frequency,
\[
\omega_n = \sqrt{\frac{K}{M}}
\]

The natural angular frequency would determine the bandwidth of the accelerometer, as shown in Figure 17.
Figure 18: Frequency Response of Accelerometer

Referring to Figure 18, the peak in the bode plot is the natural frequency of the accelerometer system, which has non-unity ratio of output over input. In order to ensure the accelerometer function in linearity region, the ratio of output is to input must be constant, which is approximately 3 Hz to 4 kHz.

When considering the electrical components of an accelerometer, the modeling is dependent on the type of accelerometer used as different type uses different electrical principal. As an example, the capacitive accelerometer is governed by the equation

\[ C = \frac{\varepsilon A}{d} \]  

which computes the capacitance between parallel plate. If the configuration used in the capacitive accelerometer is of differential capacitor as shown in Figure 19, the output voltage can then be calculated as

\[ V_o = \frac{C_1 - C_2}{C_1 + C_2} V_s \]  

Referring to Figure 20, the DRIE Bosch process first involves the process of photolithography to transfer the desired pattern on the silicon wafer. The silicon wafer may consist of two silicon wafers with an oxide layer attaching together using epoxy. Plasma etch is then used to etch vertically downward into the silicon. The ion used in the plasma etch is often sulphur hexafluoride (SF₆). Next, the sidewall of the etched region is deposited with a passivation layer, usually octafluorocyclobutane (C₄F₈) to prevent further lateral etching. These two processes are repeated until the desired depth is obtained. DRIE can produce a near vertical side wall in etch trench with high aspect ratio. In Figure 19, the oxide layer acts as an etch stop to prevent further etching of DRIE. The oxide can then be easily etched using wet etching techniques.

Figure 20: DRIE Fabrication Process in Accelerometer [4]

The DRIE process is as shown in Figure 20.

V. FABRICATION

The MEMS accelerometer can be fabricated using various fabrication techniques, depending on the geometry of the accelerometer. Each accelerometer has its own specific fabrication techniques. However, in general, stress-based accelerometers are more commonly fabricated using the bulk-micromachining as the beam suspension for supporting the seismic mass is relatively large. Displacement-based accelerometer however, can be fabricated using surface-micromachining, bulk-micromaching and LIGA.

Often in the geometry of an accelerometer, there are many movable parts. These movable parts can be patterned using deep reactive ion etching (DRIE). There are two different types of process in DRIE, which is cryogenic process and Bosch process. In cryogenic process, the wafer to be etched is cooled down to a very low temperature to reduce the rate of isotropic etching while bombarding ion at the surface which is to be etched. However, this method produces by-products that may stick to the cool surface of the silicon and hence contaminating it. The more commonly use process is the Bosch process. In Bosch process, two phases are used in alternating manner which is anisotropic etching and deposition.

Figure 21 shows another fabrication technique used to fabricate a tunneling accelerometer.
Referring to Figure 21, the SiO$_2$ is formed on the silicon wafer using epitaxial growth method. The Au is then deposited on the oxide layer using electron beam evaporation. The tip where tunneling current flows is formed using FIB lithography and ion milling. Photolithography is then used to transfer desired pattern and Au is deposited on it. To fabricate the cantilever, a sacrificial layer is formed together with photolithography to form the pattern of the cantilever. After Au is deposited for the cantilever, etch release is used to etch the sacrificial layer.

For bulk-micromachining, the process can be as shown in Figure 22. Bulk-micromachining is often used for forming support for the seismic mass in accelerometer. The piezoresistive accelerometer is one of the example, which uses bulk-micromachining to form the support of the accelerometer for detecting stress and compression caused by acceleration.

In Figure 22, the hinge commonly found in piezoresistive accelerometer is formed by first depositing photoresist on both side of the silicon wafer. Photolithography is then used to transfer pattern on both side of the silicon wafer and can be etched using wet etching techniques. The etchant used in this figure is KOH. The resulting structure is as seen in Figure 21 (d). For fabricating coils, which is found in Hall effect sensor, thin film technology is used instead.

The packaging of a MEMS accelerometer consists of only a few types as it is used more in the high-end industries as compared to commercial consumers. The packaging of the accelerometer acts as a protection to the sensor from external environment to prevent contamination of the sensor, which will affect the performance of the sensor. Since the device in the packaging is fully isolated, it is often known as hermetic packaging. Some of the packaging available for MEMS accelerometer is shown in Figure 23.

As MEMS accelerometer scaled down, it is inevitable that its package should be scaled down as well. Hence, in high density microelectronics circuit, the wafer level package (WLP) is more desirable. The packaging flow of a WLP MEMS accelerometer is as shown in Figure 24, Figure 25 and Figure 26. There are a total of three steps in the WLP of MEMS accelerometer. The first process involved the fabrication of a wafer cap, which is used to isolate the MEMS accelerometer from the surroundings. In the fabrication of the wafer cap, oxide is first grown on the silicon wafer. Then, photoresist is deposited on top of the oxide and photolithography is used to transfer pattern onto the photoresist. Once the photoresist and oxide is etched, DRIE is used to further form a deep trench until half way through the wafer. The remaining photoresist is removed before the trench is etched through using DRIE process.
Next, the oxide is completely removed, forming the desired geometry. Lastly, the silicon wafer went through oxidation to provide electrical isolation to the wafer cap. The trench form using DRIE would be used to connect the bond pad of the MEMS accelerometer to the external surroundings.

In the second process, the fabricated wafer cap will be attached to the MEMS accelerometer by using paste similar to the one used in thick film technology. However, the paste used here does not have metal and its function only as a seal for attaching the wafer cap to the MEMS accelerometer. The paste, consisting of glass for bonding purposes and organic solvent that provide the necessary viscosity is screen printed onto the wafer cap. As the wafer cap is attached to the MEMS accelerometer, it is passed though the firing process to vaporize the organic solvent and to melt the glass for bonding.

In the final sequence, TiW, Ni and Au is deposited on the wall of the via using the shadow mask. Metal is then deposited into via flowing through the via and reaching the bond pad of the MEMS accelerometer. The metal forms a solder ball on top of the wafer cap. The completed WLP is as shown in Figure 27.

Figure 27: External View of WLP [6]

Figure 28: Cross Sectional View of WLP [6]

Figure 28 shows the cross sectional view of the WLP.

VII. APPLICATION

Although accelerometer is seldom used on its own, it provides many useful functions when used together with other sensors and transducers. In the field of military, the accelerometer is integrated together with the gyroscope and other modules to form the inertial measurement unit (IMU) as shown in Figure 29. The IMU is used by the military for collecting intelligence via motion tracking.

In automobile industries, the accelerometer is used to provide safety to the car driver and passengers. It triggers the air bag system when there is a collision during an accident; prevent skidding in ABS system and constantly monitors the car suspension system. Besides that, the high end and heavy industries use accelerometer to perform vibrational test and shock test for product performance evaluation.
For example, hard disk manufacturer might use accelerometer to perform mechanical vibrational test on the hard disk to determine its performance under constant vibration. The vibrational source may come from the speaker of the laptop or any other external sources. In addition, it is also found in camera where it is used for auto positioning of the image captured and determines the orientation of the image. Furthermore, video camera uses accelerometer to provide anti shock when taking videos. Lastly, it is used widely in the entertainment field and smartphones as shown in Figure 30 for providing a more realistic gaming experience.

Table 1: Comparison between Various Sensors [5]

<table>
<thead>
<tr>
<th>Types of Sensor</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>- Easy installation</td>
<td>- Sensitive to noise (1/f noise)</td>
</tr>
<tr>
<td></td>
<td>- Have good high frequency response</td>
<td>- Requires external supply</td>
</tr>
<tr>
<td></td>
<td>- Able to withstand high temperature</td>
<td>- Requires external circuitry</td>
</tr>
<tr>
<td></td>
<td>- Miniature in size</td>
<td></td>
</tr>
<tr>
<td>Velocity Sensors</td>
<td>- Easy installation</td>
<td>- Low natural frequency</td>
</tr>
<tr>
<td></td>
<td>- Have good middle range frequency response</td>
<td>- High cross axis sensitivity</td>
</tr>
<tr>
<td></td>
<td>- No external supply is needed</td>
<td>- Requires external circuitry</td>
</tr>
<tr>
<td>Proximity Sensors</td>
<td>- Able to measure both dynamic and static</td>
<td>- Has both electrical and mechanical noise</td>
</tr>
<tr>
<td></td>
<td>displacement</td>
<td>- Requires external supply</td>
</tr>
<tr>
<td></td>
<td>- Does not wear</td>
<td>- Complex installation</td>
</tr>
</tbody>
</table>

VIII. ADVANTAGE AND DISADVANTAGE

There are many sensors which can be used for measuring the acceleration of an object other than the accelerometer. The advantages and disadvantages of these sensors are shown in Table 1.

IX. REFERENCES


