MODULE 1: PRESSURE SENSORS

Structure

Objectives

- To explain the measurement of pressure using sensors, based nanotechnology, their structure, theory of operation.

1.1 Introduction

1.Sensor

A sensor is a device used to measure the physical changes in the surroundings, like temperature, light, etc., and convert them into a readable signal.

Examples of sensors are:

- Barometer
- Accelerometer

2.Transducer

A transducer is a device that converts a non-electrical signal into an electrical signal. Transducers are referred to as energy converters.

Transducers are of different types; input transducers and output transducers.

Example of transducers are:

- Thermocouple
- Microphones

The transducer consists of a sensor and signals conditioning circuits and finds application in communication systems to convert the electricity to electromagnetic waves.

1.1.1 Comparison between Sensors and Transducers

Table 1.1: Comparison between Sensors and Transducers

Sensor	Transducer
A device that convert physical parameters to electrical output.	A device that convert energy one form to another form is know as Transducer.
The word Sensor comes from USA.	The word Transducer comes from Europe.
The uses of Sensor is for sensing element itself.	The uses of transducer is for sensing element and also for circuitry.
In Sensor changes its resistance with temperature.	In Transducers change in resistance to change in voltage.
All the sensors are not transducers.	**All Transducers contain a Sensor.**
It is a sensor when it responds to a stimulus.	It becomes transducers when connected in a bridge circuit.
It detects change in physical stimulus and turn it into a signal.	It transfers power form one system to another in the same or in different form.
Examples of Sensor: Temperature Sensor, and Proximity Sensor.	Example of Transducer: Strain gauge, and Piezoelectric Transducer.

1.1.2 PARTS OF TRANSDUCER

The transducer consisting of two important and closely related parts

- **Sensing or Detection Element**: A detector or a sensing element is that part of a transducer which responds to a physical phenomenon or a change in physical phenomenon. The response of sensing element must be closely related to physical phenomenon.
- **Transduction Element**: A transduction element is one which transforms the output of a sensing element to an electrical output.

1.2 Classification of Transducers

Transducers are classified based on:

1. On the basis of transduction form used

2. As primary and secondary transducers

3. As passive and active transducers

4. As analog and digital transducers

5. As transducers and inverse transducers

1. Classification based on the principle of transduction form used:

This classification is based on the principle of transduction as resistive, inductive, capacitive etc. depending upon their conversion into resistance, inductance or capacitance respectively. They can be classified as thermoelectric, piezoelectric, electro-kinetic, optical and magneto restrictive.

- Resistance - Potentimeter devices, Resistance strain gauge, Pirani guage or hot wire meter, Resistance thermometer, Thermistor, Resistance hygrometer, Photoconductive cell.
- Capacitance - Variable capacitance pressure gauge, Capacitor microphone, Dielectric gauge.
- Inductance - Magnetic circuit transducer, Reluctance pick-up, Differential transformer, Eddy current guage, Magneto striction gauge.
- Voltage & Current - Hall effect transducer, Ionisation chamber, Photo emissive cell, Photomultiplier tube.
- Self-generating transducers - Thermocouple, Thermopile, Moving coil generator, Piezoelectric transducer,
- Photovoltaic.

2. Classification as primary and secondary transducers

Primary transducer senses the input directly and physical phenomenon is converted into the electrical form directly. While in secondary transducer, initially input is being sensed by some detector or sensor and then its output in some form other than input signal is given to transducer to convert into electrical signal. Mechanical device acts as a primary detector transducer and the electrical device acts as the secondary transducer in most of the measurement systems with mechanical displacement serving as the intermediate signal.

Example of Primary and secondary transducer Primary transducer Displacement voltage Secondary transducer

3. Classification as Active and Passive transducer

Active transducers are one which develop their output in the form of electrical voltage or current without any auxiliary source. They are also called self-generating transducers. Active transducers draw energy from the system under measurement and such transducers normally give very small output. Thermocouples used for the measurement of temperature, tacho-generators used for the measurement of angular velocity comes under this category.

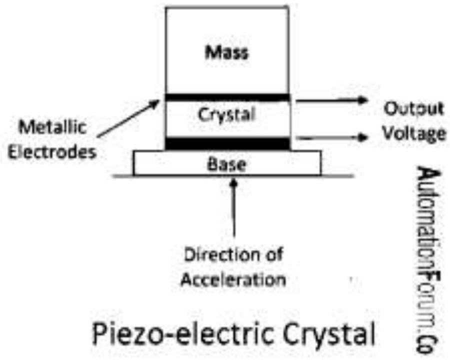


Fig1.1: Piezoelectric Crystal

In the example shown in Fig.1.1, the crystal is sandwiched between 2 metallic electrodes, and the entire sandwich is fastened to a base which may be the floor of a rocket. On the top of the sandwich a fixed mass is placed which exerts a certain force due to acceleration on the crystal due to which a voltage is generated. The voltage output is proportional force and hence is proportional to acceleration. The property of piezo -electric crystal is that when a force is applied to them, they produce an output voltage

Eg: Moving coil, Piezoelectric crystal, Thermocouple, Photovoltaic cell

Passive transducers are one which require external power source for energy conversion. In passive transducers electrical parameters like resistance, inductance, capacitance causes a change in voltage, current or frequency of external source. Resistive, inductive and capacitive transducers fall in this category.

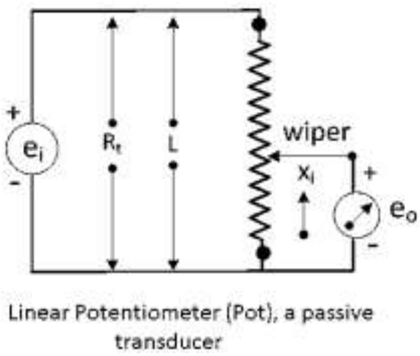


Fig1.2: Linear Potentiometer

This is an example for passive transducer. A linear potentiometer is a resistive transducer powered by a source voltage ei and is used for the measurement of linear displacement xi.

Eg: Resistive, Capacitive, Inductive.

4. Analog and Digital transducer

Transducers, on the basis of nature of output can be classified as analog and digital.

Analog transducers: These type of transducers which convert input signal into output in the form of a continuous function of time such as thermistor, LVDT, thermocouple etc.

Eg: Strain gauge, LVDT, Thermocouple, Thermistor.

Digital transducers: These type of transducers which convert input signal into output in the form of pulses. The examples of digital transducers are linear displacement transducers using conducting and non-conducting contacts, opaque and translucent segments and shaft encoders. It can be easily represented by opaque and transparent areas on a glass scale or non-conducting and conducting areas as the binary system uses only two symbols 0 and 1.
Eg: Glass scale, Metallic scale.

5. Transducers and Inverse transducers

The basic requirement for control of physical quantities such as position, speed, temperature pressure and flow rate in an industrial plant is the ability to measure these quantities. The control action is only possible if the physical quantity can be measured. Transducers as early mentioned converts a non-electrical quantity into electrical whereas inverse transducers converts an electrical quantity into some other forms.

Eg: Peizo electrical crystal.

1.3 Advantages and Disadvantages of Electrical Transducers

Basically, there are two types of transducers, electrical, and mechanical.
An **electrical transducer** is a sensing device by which the physical, mechanical or optical quantity to be measured is transformed directly by a suitable mechanism into an electrical voltage/current proportional to the input measurand.

1.3.1 Advantages of Electrical Transducer

The main advantages of electrical transducer (conversion of physical quantity into electrical quantities) are as follows:

1. Electrical signal obtained from electrical transducer can be easily processed (mainly amplified) and brought to a level suitable for output device which may be an indicator or recorder.

2. The electrical systems can be controlled with a very small level of power
3. The electrical output can be easily used, transmitted, and processed for the purpose of measurement.
4. With the advent of IC technology, the electronic systems have become extremely small in size, requiring small space for their operation.
5. No moving mechanical parts are involved in the electrical systems. Therefore there is no question of mechanical wear and tear and no possibility of mechanical failure.

1.3.2 Disadvantages of Electrical Transducer

1. The electrical transducer is sometimes less reliable than mechanical type because of the ageing and drift of the active components.
2. Also, the sensing elements and the associated signal processing circuitry are comparatively expensive.
3. With the use of better materials, improved technology and circuitry, the range of accuracy and stability have been increased for electrical transducers.
4. Using negative feedback technique, the accuracy of measurement and the stability of the system are improved, but all at the expense of increased circuit complexity, more space, and obviously, more cost.

1.4 Transducers Actuating Mechanisms, Resistance Transducers

Transducer actuating mechanism

An actuating mechanism usually consists of a motor, a transmission, and control units, as well as feedback, signalling, interlocking, and shutoff units. Actuating mechanisms to control the flow of fluids or gases consist of a valve, shutter, or gate, which is moved by hydraulic, pneumatic, or electrical drive.

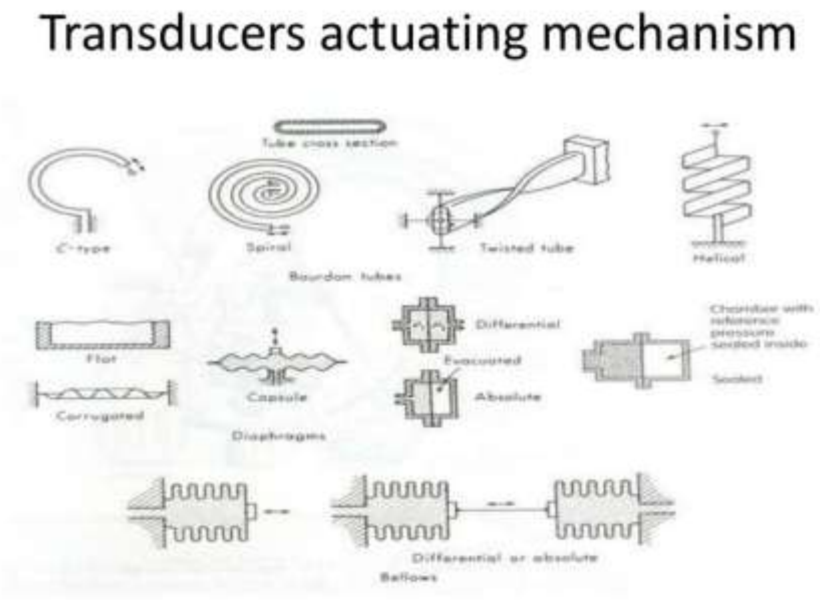


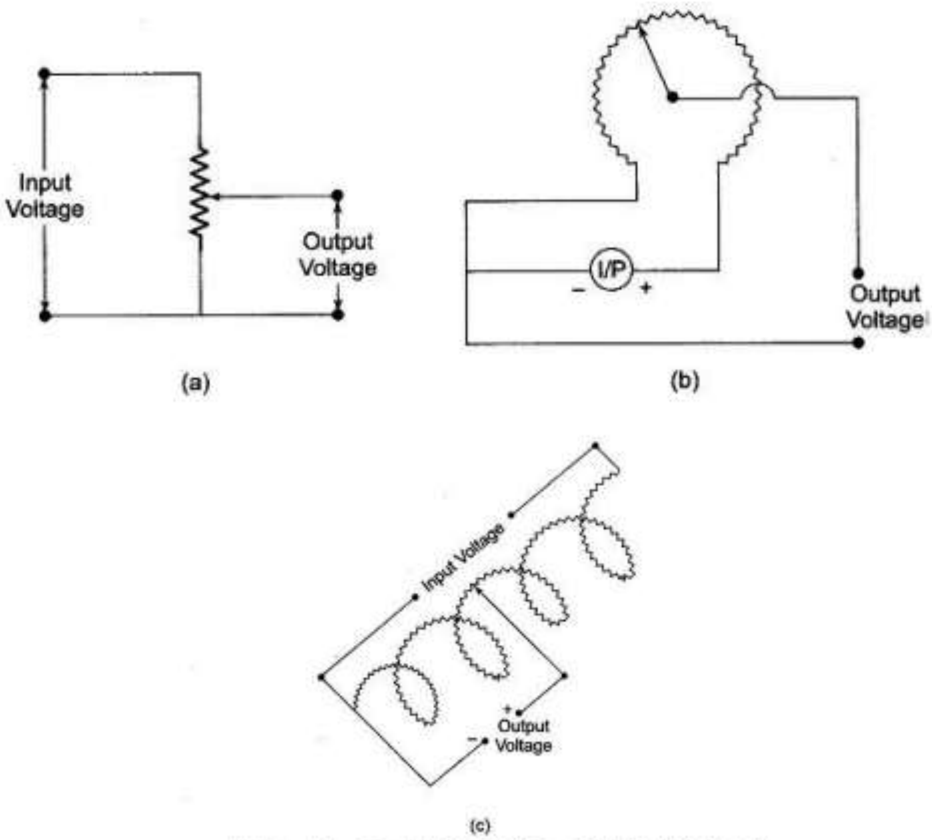
Fig1.3: Transducer actuating mechanism

1.4.1 Resistive Transducer

1. Resistive Transducer Definition are those in which the resistance changes due to a change in some physical phenomenon. The change in the value of the resistance with a change in the length of the conductor can be used to measure displacement.
2. Strain gauges work on the principle that the resistance of a conductor or semiconductor changes when strained.
3. This can be used for the measurement of displacement, force and pressure. The resistivity of materials changes with changes in temperature. This property can be used for the measurement of temperature.

1.4.2 Potentiometer

1. A resistive potentiometer (pot) consists of a resistance element provided with a sliding contact, called a wiper. The motion of the sliding contact may be translatory or rotational.
2. Some have a combination of both, with resistive elements in the form of a helix, as shown in Fig. They are known as helipots. Translatory resistive elements, as shown in Fig. a), are linear (straight) devices. Rotational resistive devices are circular and are used for the measurement of angular displacement, as shown in Fig.(b).
3. Helical resistive elements are multi turn rotational devices which can be used for the measurement of either translatory or rotational motion.
4. A potentiometer is a passive transducer since it requires an external power source for its operation.



(a) Translatory Type (b) Rotational Type (c) Helipot (Rotational)

Fig1.4: Transducer actuating mechanism types

1.4.3 Resistance Pressure Transducer

1. Measurement in the resistive type of transducer is based on the fact that a change in pressure results in a resistance change in the sensing elements. Resistance pressure transducers are of two main types.
2. First, the electromechanical resistance transducer, in which a change of pressure, stress, position, displacement or other mechanical variation is applied to a variable The other resistance transducer is the strain gauge, where the stress acts directly on the resistance. It is very commonly used for stress and displacement measurement in instrumentation.
3. In the general case of pressure measurement, the sensitive resistance element may take other forms, depending on the mechanical arrangement on which the pressure is caused to act.
4. Figure shows two ways by which the pressure acts to influence the sensitive resistance element, i.e. by which pressure varies the resistance They are the bellow type, and the diaphragm type. (Yet another is the Bourdon tube of pressure gauge).
5. In each of these cases, the element moved by the pressure change is made to cause a change in resistance.
6. This resistance change can be made part of a bridge circuit and then taken as either ac or dc output signal to determine the pressure indication.

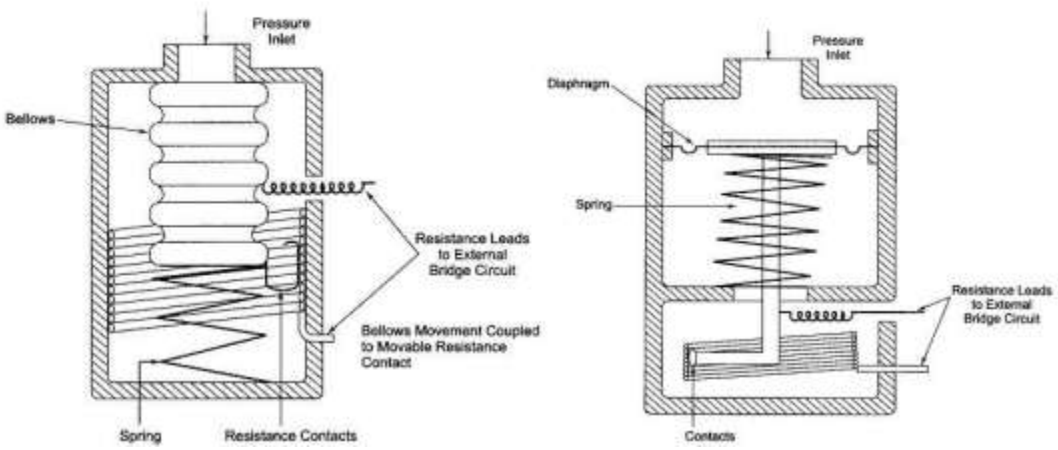


Fig 1.5 : Resistance Pressure Transducer; Sensitive diaphragm moves the resistance contact

1.5 Capacitive Pressure Sensors

Among the pressure sensors that are widely used in the industry, capacitive pressure sensors are particularly noteworthy.

These sensors are characterized by

- **Very low temperature hysteresis** and
- **Pressure hysteresis**
- **Low power consumption**

Traditional capacitive pressure sensors, however, suffer from inherently **poor resolution**

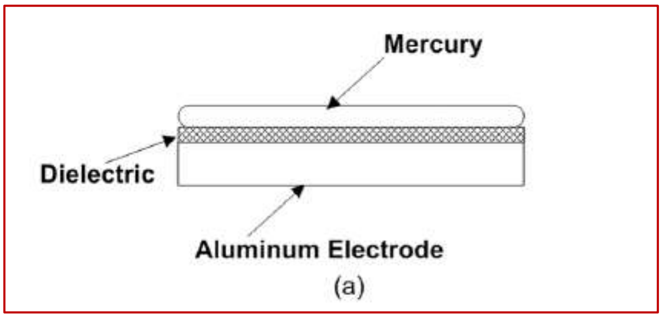
New capacitive pressure sensors with extremely high resolution and sensitivity, based on nanotechnology

Structure

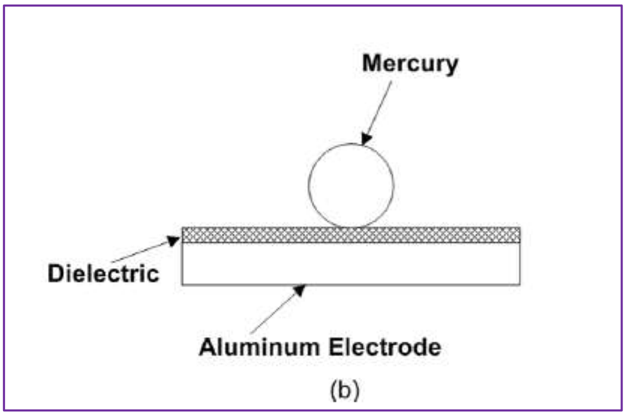
- The recently introduced mercury-droplet capacitive pressure sensor has demonstrated a change in capacitance of approximately 6.73 μF over a pressure range of 0 to 3 kPa.
- The sensitivity of this type of sensor is therefore 2.24 μF/kPa, substantially higher than any of the known types of capacitive pressure sensors.
- The basic concept of the new sensor is to mechanically deform a drop of mercury that is separated from a flat aluminum electrode by a very thin layer of a dielectric material, so as to form a parallel-plate capacitor where the electrode area is variable to a high degree.
- This principle is illustrated in Figure 1.1
- The principle of the new device, therefore, is to create a capacitor with a variable electrode area, rather than a variable inter electrode spacing

(a) A drop of mercury is flattened against an aluminum electrode that is covered with a layer of a dielectric material.

A parallel-plate capacitor with one liquid electrode is formed.



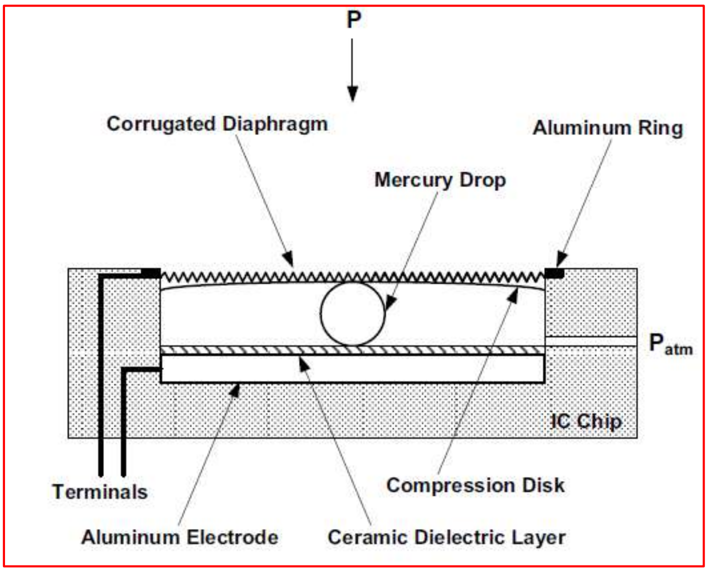
(b) Under zero pressure, the mercury drop returns to its nearly spherical shape. The change in capacitance between the two configurations (which is proportional to the change in the contact area of the liquid electrode) can be several hundred fold



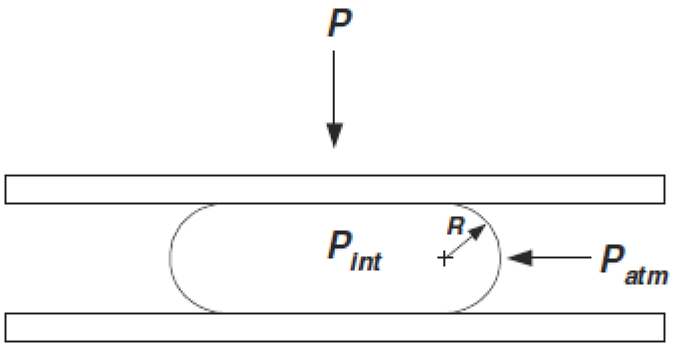
The drawback, however, is that the <u>maximum temperature-related error</u> is slightly worse than that of the other capacitive pressure sensors (due to the thermal expansion of the mercury droplet, particularly at high temperatures)

	Sensitivity	Linearity	Pressure Hysteresis	Temperature Hysteresis (For temp. range of −10°C to +80°C)
Piezoresistive pressure sensors	Up to 25 mv/kPa	Generally linear	Up to ± 1% FSO	Up to ± 2% FSO
Capacitive pressure sensors	Up to 0.2 nF/kPa	Generally nonlinear	Up to ± 0.1% FSO	Up to ± 0.5% FSO
New sensor (uncompensated)	2.24 μF/kPa	Nonlinear	Less than ± 0.05% FSO	Up to ± 1.5% FSO

Mechanical structure of the sensor



Step-1:A drop of mercury of a 3 mm diameter is placed on top of a flat aluminum electrode that is covered with a 1 µm thick layer of a ceramic material that has a very high dielectric constant
Step-2:The drop is held in place by means of an aluminum disk that serves as the compression mechanism
Step-3: The compression disk, in turn, is acted upon by means of a corrugated stainless steel diaphragm,
Step-4: The compression disk is given a slight curvature, as shown in the figure, such that the spacing between the disk and the ceramic layer is exactly 3 mm at the center, but less than 3 mm everywhere else. In this manner, the mercury drop will be forced to the center each time the stainless steel diaphragm retracts.
Step-5: The diaphragm is held in place by means of a thin aluminum ring
Step-6: The entire assembly is mounted inside an open-cavity, 24-pin DIP IC package.
Step-7: Since the air that surrounds the mercury droplet must be allowed to exit from the sensor and re-enter as the sensor is pressurized/depressurized, an atmospheric
pressure relief conduit is drilled in the IC package,
In **applications** where it is desired to detect pressures that are lower than the atmospheric pressure at sea level (like aircraft altitude applications, for example), then a suitable vacuum can be initially applied to the pressure relief conduit
Theory



Pressures and geometry in the deformation of a drop of mercury

Step-1: Figure shows the geometry of a drop of mercury that is deformed between two solid surfaces.

Step-2: The vertical pressure that is acting on the drop is *P*, and the lateral pressure is the atmospheric pressure *Patm*.

Step-3: *Pint* is the internal pressure, and *R* is the radius of curvature of the part of the surface of the liquid that is not flattened

Step-4: The internal pressure *Pint* in the liquid must be balanced by the atmospheric pressure

plus the **Laplace pressure, or the pressure due to surface tension**

$$\boxed{P_{int} = P_{atm} + \frac{2\gamma}{R}}$$

where 2Y /*R* is the Laplace pressure and g is the surface tension of mercury

Step-5: As the drop of mercury is flattened, the difference in the internal pressure will be equal to the applied pressure *P*,

$$\boxed{P = P_{int} - (P_{int})_0}$$

where (*Pint*)0 is the internal pressure at zero applied pressure

By using Eq. (1.1), Eq. (1.2) can be written as follows:

$$\boxed{P = P_{atm} + \frac{2\gamma}{R} - \left(P_{atm} + \frac{2\gamma}{R_0}\right)}$$

where *R*0 is the original unflattened radius of the drop

$$\boxed{P = 2\gamma\left(\frac{1}{R} - \frac{1}{R_0}\right)}$$

The capacitance of a parallel plate capacitor is

$$\boxed{C = \frac{\varepsilon A}{d}}$$

where e is the permittivity of the dielectric medium,

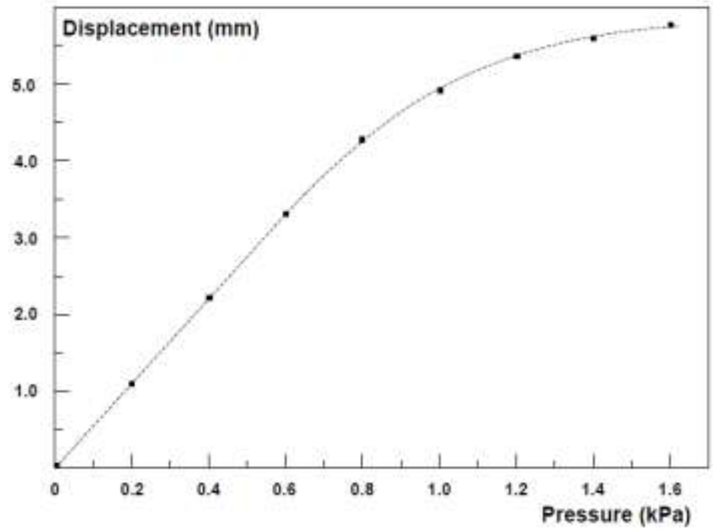
A is the surface area of the

electrodes, and *d* is the thickness of the dielectric

Calculating the wetting area of the deformed droplet is a simple but rather lengthy and uninformative exercise

$$A = \pi \left[\sqrt{\frac{\pi^2 R^2}{16} + \frac{2R_0^3}{3R}} - \frac{\pi}{4} R \right]^2$$

where *R* is the radius of curvature of the part of the surface of the liquid that is not flattened



the relationship between the applied pressure and the capacitance can be easily determined as well. That relationship can be represented as

Pdia =*αC*

where *Pdia* is the pressure acting on the diaphragm and a is the constant of proportionality.

The physical, or total, pressure acting on the sensor is equal to the sum of the two pressures

$$P_{total} = \alpha C - \frac{2\gamma}{R_0} + 2\gamma / \left(\sqrt{\frac{Cd}{\varepsilon \pi^3} + \frac{4}{3} R_0^3 \left(\frac{\varepsilon}{\pi C d} \right)^{1/2}} - \sqrt{\frac{Cd}{\varepsilon \pi^3}} \right)$$

Temperature related errors

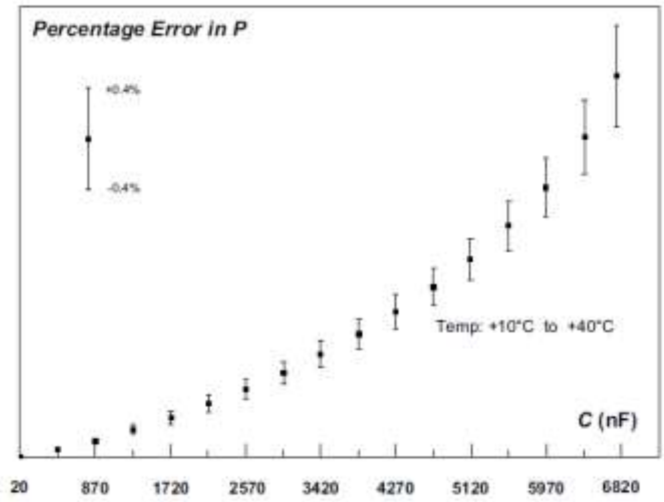
For large changes in temperature, the error in the calculated pressure for the present sensor is actually slightly higher than other known types of capacitive pressure sensors due to the thermal expansion of the drop of mercury

$$L = L_0 \left(1 + \lambda \Delta T\right)$$

where L is any linear dimension, λ is the metal's expansion coefficient, and ΔT is the change in temperature.

Pressure hysteresis:

The hysteresis in the values of the calculated pressure is determined by **cycling the pressure at a fixed temperature** and plotting the measured pressure versus the actual applied pressure.



Susceptibility to mechanical shocks:

If the sensor is shocked, the mercury drop will be **momentarily displaced** (especially if a small pressure is acting on the drop), and it was observed that a "recovery time" is needed for the drop to return to its original position (and hence for the momentary error to disappear).

Environmental effects:

At elevated temperatures (a few hundred °C), mercury reacts with the oxygen in the air to form mercury oxide.

The presence of **mercury oxide can severely degrade the performance of the sensor**.

Generally, the use of this sensor at temperatures above +80°C is not recommended.

1.6 Inductive Pressure Sensors,

Pressure sensors exist in mainly two varieties: **piezo-resistive and capacitive**.

Piezoresistive pressure sensors are characterized by **good linearity** and **acceptable sensitivity**, but the temperature hysteresis in these sensors is usually quite large

The sensor is characterized by

(1) miniature size (the sensor fits inside an IC package);

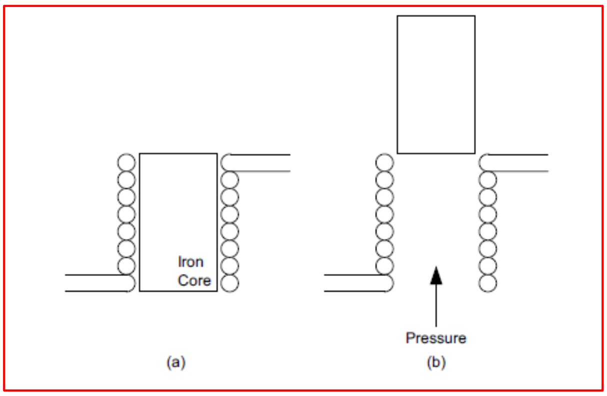
(2) Excellent linearity over an arbitrarily chosen pressure range;

(3) substantially high sensitivity;

(4) substantially low temperature hysteresis.

Structure

The principle of the new device



Step-1: The change in inductance is equal to the **relative magnetic permeability** of the core material

Step-2: (a) A movable iron core is positioned inside the core of a vertical inductor (coil).

Step-3: (b) As pressure acts on the iron core in the **vertical direction**, the core can be totally displaced outside the coil.

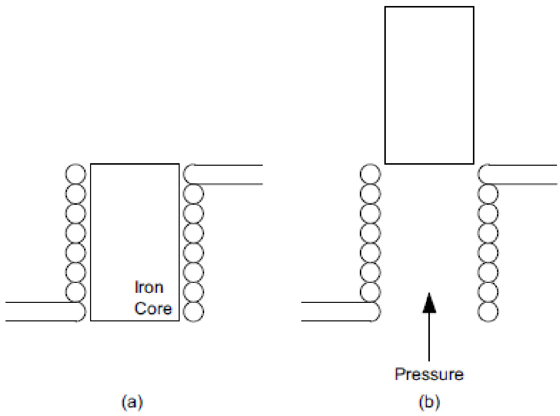
Step-4: The change in inductance between the two configurations is equal to the **relative magnetic permeability of the core material** and is typically 4000-fold or higher.

Structure

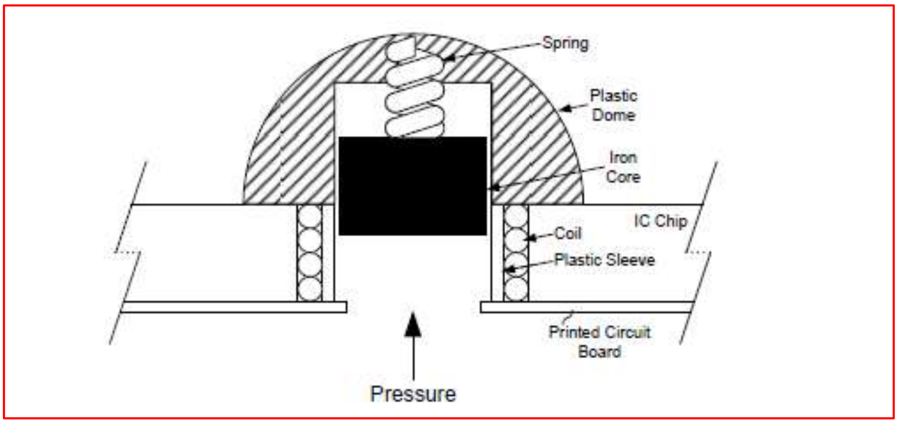
The principle of the new device

Step-5: By comparison with the LVDT, this sensor offers substantially higher sensitivity, does not require AC excitation

A change in inductance of approximately 34.5 mH over a pressure range of 0.3 to 10 kPa.



Structure



Mechanical structure of the sensor

Step-1: A vertical coil of a height of 4 mm and a diameter of 12 mm is totally embedded inside an open-cavity, 24-pin DIP IC package

Step-2: A small cylindrical iron core of a height of 4 mm and a diameter of 6 mm is positioned

inside the coil, surrounded by a smooth Teflon sleeve

Step-3: In the device shown, the pressure acts on the iron core in the upward direction.

Step-4: Semi-spherical plastic dome is positioned on top of the coil in order to contain the iron core it displaced

Step-5: In the internal cavity of the dome, a spring with a known spring constant is mounted.

Step-6: As the displaced iron core exerts force on the spring, the displacement will be proportional to the force (and hence pressure) that is acting on the iron core.

Step-7:The displacement of the iron core, in addition, will be related to the observed inductance of the coil.

Theory

Inductance as a function of the position of the iron core:

The inductance *L* of any inductor is given by the well-known equation

$$L = \frac{\mu_0 \mu_r N^2 A}{l}$$

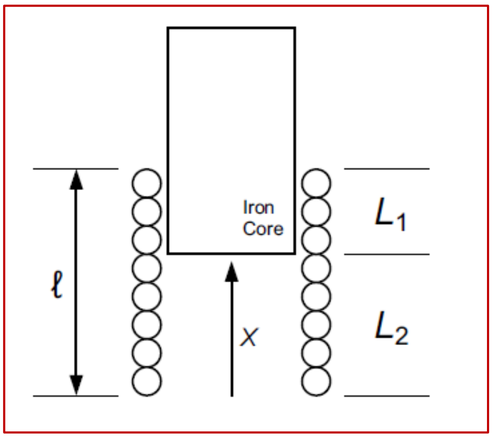
where **μ0** is the magnetic permeability of free space,

μr is the relative permeability of the material present in the core,

N is the number of turns in the coil,

A is the cross sectional

area of the coil, and ***l*** is its length.



Step-1: Figure shows the creation of two inductors in series as the iron core is displaced by a small distance x from its original position.

Step-2: The first inductor contains the iron core and its inductance is labeled $L1$, and the second inductor contains only air in its core and its inductance is labeled $L2$. the inductances $L1$ and $L2$ will be now given in terms of the displacement x as follows:

$$L_1 = \frac{\mu_0 \mu_r N_1^2 A}{(l-x)}$$

$$L_2 = \frac{\mu_0 N_2^2 A}{x}$$

where $N1$ is the number of turns in the first inductor and $N2$ is the number of turns in the second inductor

The following two relationships now hold

$$N_1 + N_2 = N$$

$$\frac{N_2}{N} = \frac{x}{l}$$

These two relationships can be alternatively written as follows:

$$N_1 = N\left(1 - \frac{x}{l}\right)$$

$$N_2 = N\left(\frac{x}{l}\right)$$

By substitution for $N1$ and $N2$ from the above two identities

$$L_1 = \frac{\mu_0 \mu_r N^2 A}{l}\left(1 - \frac{x}{l}\right)$$

$$L_2 = \frac{\mu_0 N^2 A x}{l^2}$$

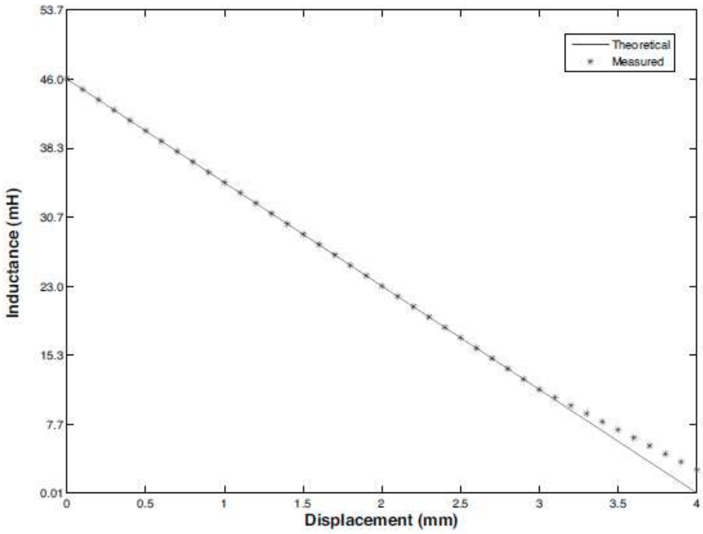
total inductance of a series combination of two inductors is equal to the sum of the individual inductances

$$L = L_1 + L_2 = \frac{\mu_0 N^2 A}{l}\left[\mu_r - \frac{x}{l}(\mu_r - 1)\right]$$

$$= L_0\left[\mu_r - \frac{x}{l}(\mu_r - 1)\right]$$

where L is the total observed inductance and
$L0$ is the inductance of the coil with an
air core (minimum inductance)

plot of L as a function of the displacement x



inductance varies linearly from a maximum value *Lmax* (inductance of the coil with iron core) to a minimum value *L*0

Position of the iron core as a function of the applied pressure:

Step-1: In the present prototype, the pressure acts on the iron core in the upward direction.

Step-2: Accordingly, a minimum force *Fmin* = *mg* must be applied, where *m* is the mass of the iron core and *g* is the acceleration of gravity.

$$P_{min} = \frac{F_{min}}{A}$$

Step-3: The sensor cannot respond to any pressure less than *Pmin* equal to 0.3 kPa in the present prototype

Step-4: Pressures larger than *Pmin* will result in a force that will compress the vertical spring The net force acting to compress the spring will be given by

$$F = kx = (P - P_{min})A$$

where k is the spring constant and P is the pressure acting on the sensor
The displacement x of the iron core will be given as a function of pressure by

$$x = \frac{(P - P_{min})A}{k}$$

$$x = \frac{(P - P_{min})A}{k}$$

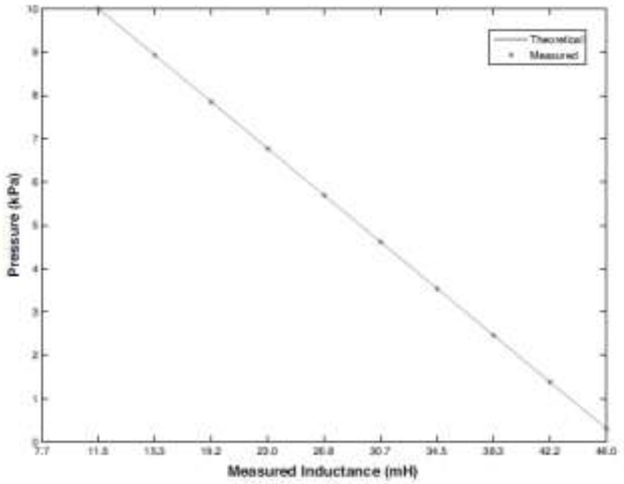
Applied pressure as a function of the observed inductance L:
We obtain a relationship between L and the applied pressure:

$$L = L_0 \left[\mu_r - (\mu_r - 1)\frac{(P - P_{min})A}{kl} \right]$$

Solving for P, we obtain

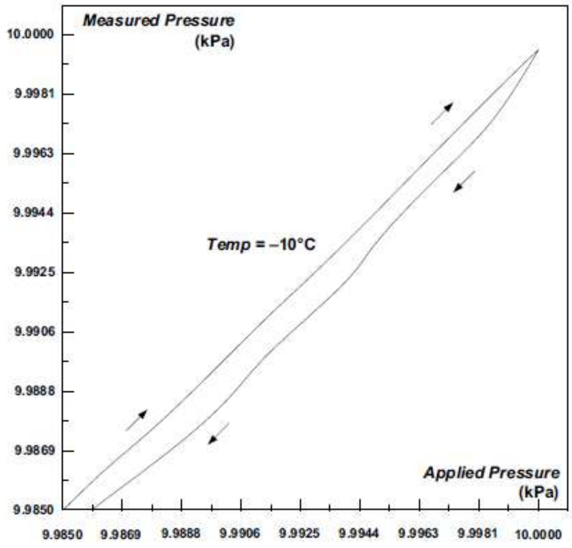
$$P = P_{min} + \frac{kl}{A}\left(\frac{\mu_r - L/L_0}{\mu_r - 1}\right)$$

Pressure P as a function of the measured inductance L.



Pressure hysteresis:

The hysteresis in the values of the calculated pressure was determined by cycling the pressure applied to the sensor at a fixed temperature and plotting the measured pressure versus the actual applied pressure



(a)

The maximum hysteresis error was found to be +/-0.05%

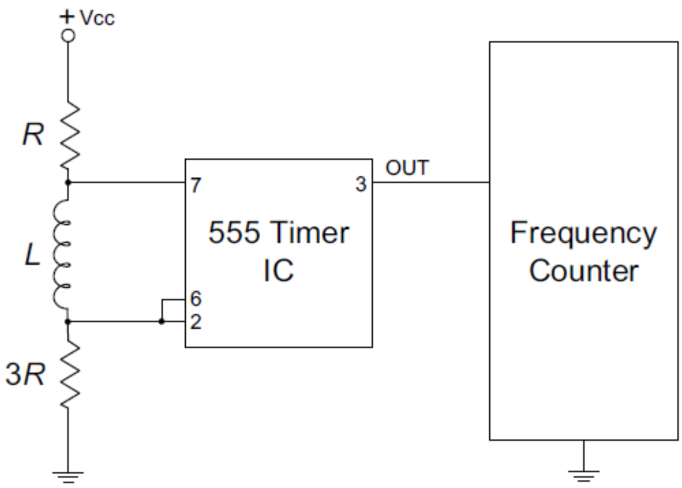
Temperature hysteresis:

The maximum temperature hysteresis error is about +/- 1%

Susceptibility to mechanical shocks:

If the sensor is shocked in the vertical direction, the iron core will be momentarily displaced, and it was observed that a "recovery time" is needed for the iron core to return to its original position

Sensor Interface Circuit

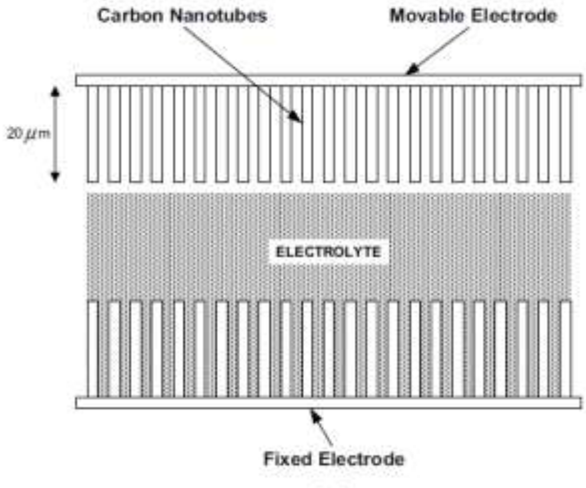


1.7 Ultrahigh sensitivity Pressure sensors

Recent trends in **earthquake monitoring** and prediction have created a requirement for a highly sensitive vibration detector.

In addition, a **highly sensitive pressure sensor** (a sensor with a capability to detect pressures of less than one Pascal) will be very useful for a new class of biological and molecular sensing applications

Structure

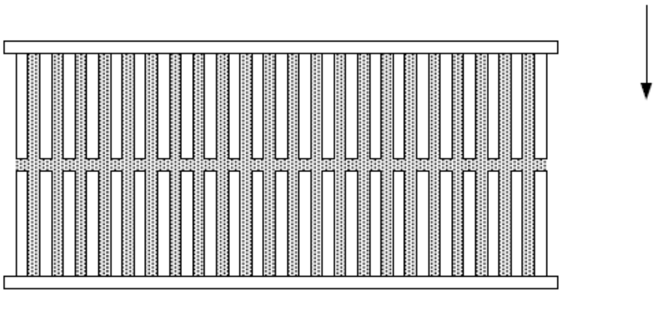


(a)

Step-1: The basic idea behind the new sensor is to create a transduction mechanism that uses a variable ultracapacitor rather than a variable capacitor

Step-2: In this mechanism, an extremely small displacement of 20 μm (less than the width of a human hair) triggers a substantially large variation in capacitance.

Step-3: (a) An ultracapacitor consisting of two electrodes is assembled such that one electrode is fixed and is fully immersed in the electrolyte while the other electrode is movable and is initially positioned outside of the electrolytic solution



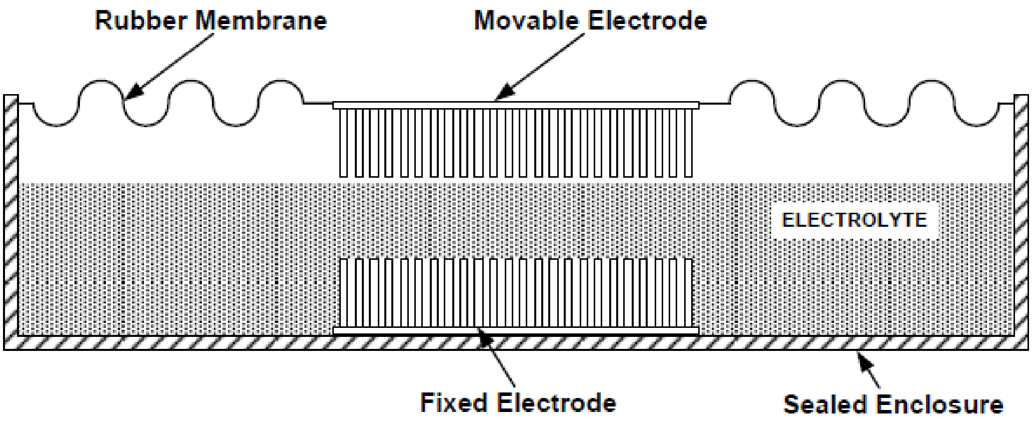
(b)

Step-4: Each electrode consists of a stainless steel plate on which carbon nanotubes of a length of approximately 20 μm are grown

Step-5: (b) As pressure or vibration is applied, the
movable electrode travels downward and dips into the electrolytic solution

Step-6: As the electrode travels a distance of 20 μm(the length of the carbon nanotubes), the capacitance increases from zero to full capacitance (approximately 54 μF

Mechanical Structure



Step-1: Figure is a mechanical diagram showing the actual construction of the sensor.
Step-2: The rubber membrane to which the movable electrode is attached acts as a spring mechanism that permits the movable electrode to retreat back to its original position.
Step-3: The rubber membrane used is
actually conductive rubber, and therefore there is no need to connect a wire terminal
directly to the movable electrode
Step-4: The fixed electrode (not shown in the picture) is mounted underneath the movable electrode and is connected to its own terminal.
Step-5: The entire sensor is housed inside an off-the-shelf stainless steel enclosure that provides two external terminals for easy connection to other circuitry.

Theory

Sensing of pressure:

The surface area *A* of the CNTs that is immersed in the electrolyte will be given by

$$\boxed{A = N \times 2\pi r x}$$

where *N* is the total number of CNTs on the surface of the electrode,
r is the radius of one carbon nanotube, and

x is the displacement of the electrode

The overall capacitance *C* of the ultra-capacitor is a series combination of the capacitances at each of the electrode–electrolyte interfaces

$$\boxed{C = \frac{1}{2}\frac{\varepsilon_0 \varepsilon_r A}{d}}$$

The pressure acting on the sensor is simply given by the ratio

$$\boxed{P = \frac{F}{A_{electrode}}}$$

where *Aelectrode* is the area of the movable electrode.

Sensing of vibrations:

When the sensor is subjected to vibration, the moving electrode can be modeled as a forced harmonic oscillator

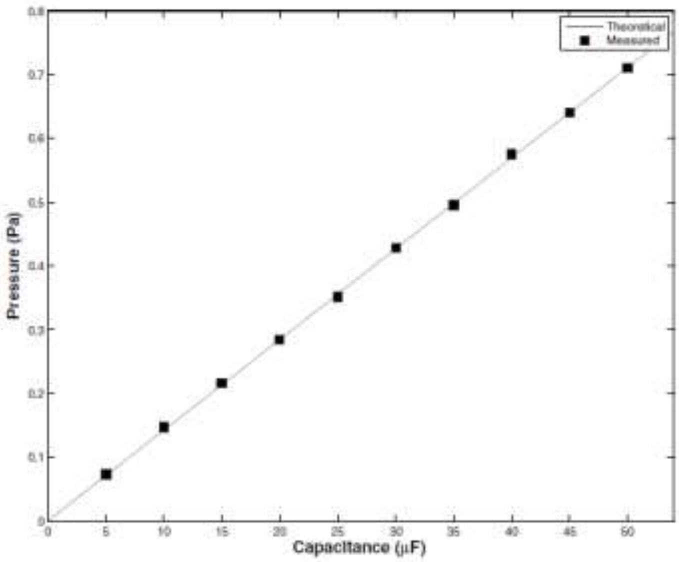
$$\boxed{x(t) = \frac{F_{max} \sin \omega t}{m\sqrt{(\omega_0^2 - \omega^2)^2 + \beta^2 \omega^2}}}$$

where *m* is the mass of the oscillator (the electrode),

$$\omega_0 = \sqrt{k/m}$$ is the natural frequency of oscillation

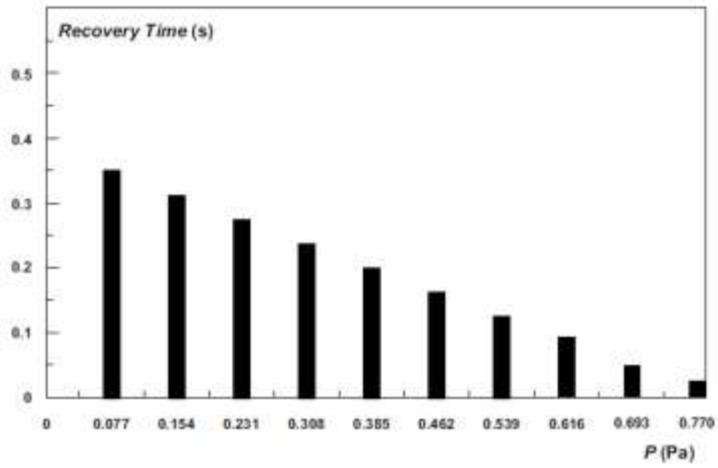
is the damping coefficient

Pressure measurement:



Pressure acting on the sensor as a function of the measured capacitance

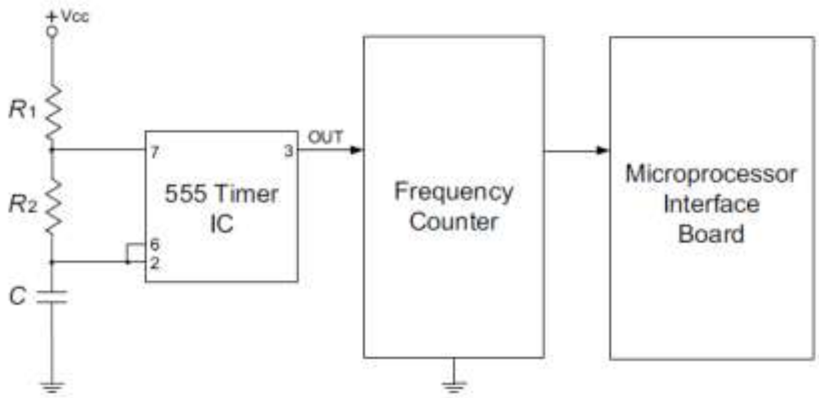
Acceleration measurement:



After-shock recovery time as a function of the applied pressure

The sensor was subjected to vibrations at a frequency of 14 Hz on the electrodynamic shaker

Block diagram of the interface circuit used to measure the capacitance *C*.



Outcomes

At the end of the module, students will be able to:

CO-1: Interpret the application of various sensors and transducers and illustrate the working of capacitive and Inductive pressure sensor based on nanotechnology. [L3] M-1

TEXT BOOKS:

1. Micro- and Nano-Scale Sensors and Transducers, By Ezzat G. Bakhoum, CRC Press, 1st Edition,2015.

Reference Books

1. Electrical and Electronic Measurements, R.K Rajput, S. Chand, 3rd Edition, 2013
2. A Course in Electronics and ElectricaL, J.B. Gupta, Katson Books, 13th Edition, 2008
3. A Course in Electrical and Electronic Measurements and Instrumentation, A. K. Sawheny, DhanpatRai,
4. https://onlinecourses.nptel.ac.in/noc21_ee26/preview
5. https://nptel.ac.in/courses/108108147