Mechanical Measurements & Metrology

CHARACTERISTICS OF MEASUREMENT SYSTEM

CHARACTERISTICS OF MEASUREMENT SYSTEMS

- A knowledge of the performance characteristics of an instrument is essential for selecting the most suitable instrument for specific measuring jobs
- The performance characteristics may be broadly divided into two groups, namely

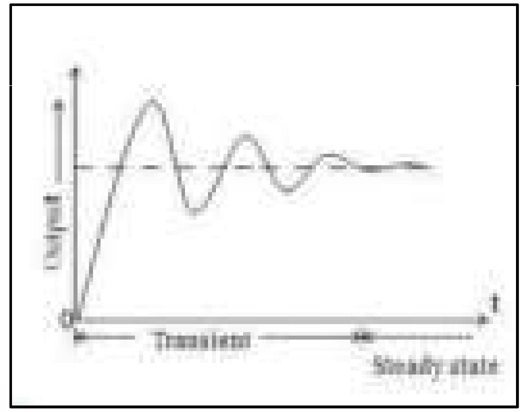
    Static characteristics

    Dynamic characteristics

STATIC and DYNAMICS CHARACTERISTICS OF MEASUREMENT SYSTEMS

Characteristics of Measurement devices

- **Static:** concerned only with the steady-state reading that the instrument settles down to, such as the accuracy of the reading etc.
- **Dynamic:** describe then transient behavior between the time a measured quantity changes value and the time when the instrument output attains a steady value in response.

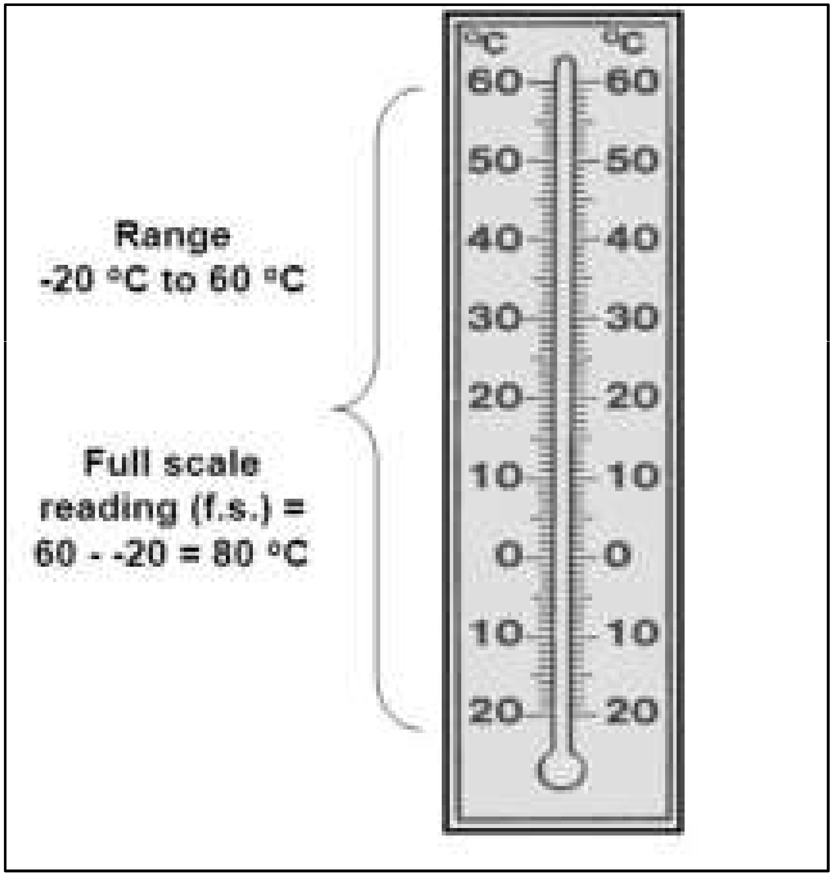


STATIC PERFORMANCE OF INSTRUMENT

- Static characteristics of an instruments are concerned only with steady state readings
- *Accuracy and Precision*
- *Range or Span*
- *Linearity & Sensitivity*
- *Repeatability*
- *Reproducibility*
- *Hysteresis*
- *Threshold*
- *Resolution*
- *Dead space*

RANGE OR SPAN AND FULL SCALE

- The range or span of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure



Example: A particular micrometer is designed to measure dimensions between 50 and 75 mm. What is its measurement range?

Ans: The measurement range is simply the difference between the maximum and minimum measurements. (25 mm)

ACCURACY

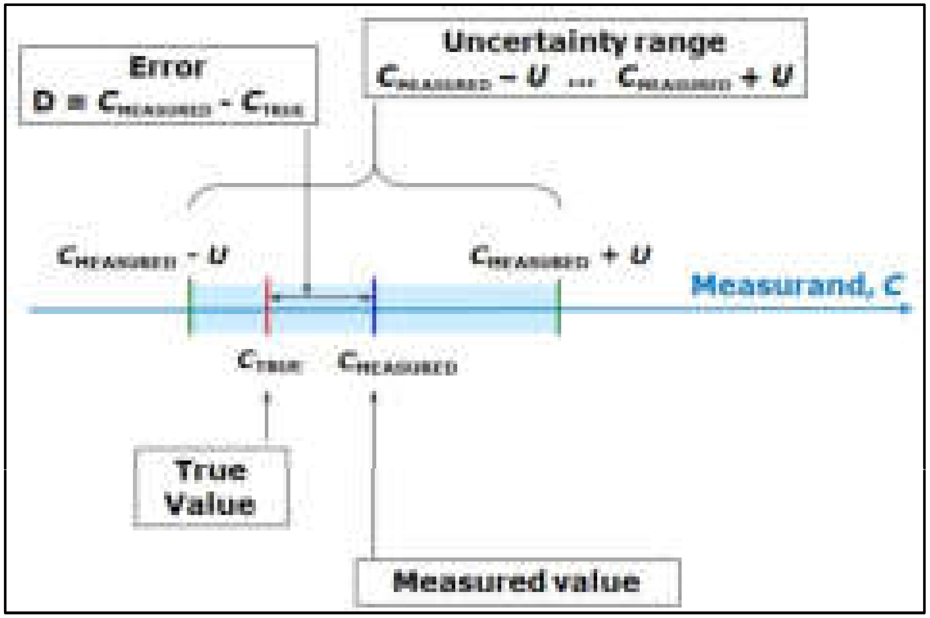
- The accuracy of an instrument is a measure of how close the output reading of the instrument is to the true value
- In practice, it is more usual to quote the inaccuracy or measurement uncertainty value rather than the accuracy value of an instrument
- Inaccuracy or measurement uncertainty is often quoted as a percentage of the full-scale reading of an instrument
- Accuracy can be improved by calibration

A pressure gauge with a measurement range of 0–10 bar has a quoted inaccuracy of ±1.0% of the full-scale reading.

(a) What is the maximum measurement error expected for this instrument?

(b) What is the likely measurement error expressed as a percentage of the output reading if this pressure gauge is measuring a pressure of 1 bar?

ERROR and UNCERTAINTY



Uncertainty in a Measurement

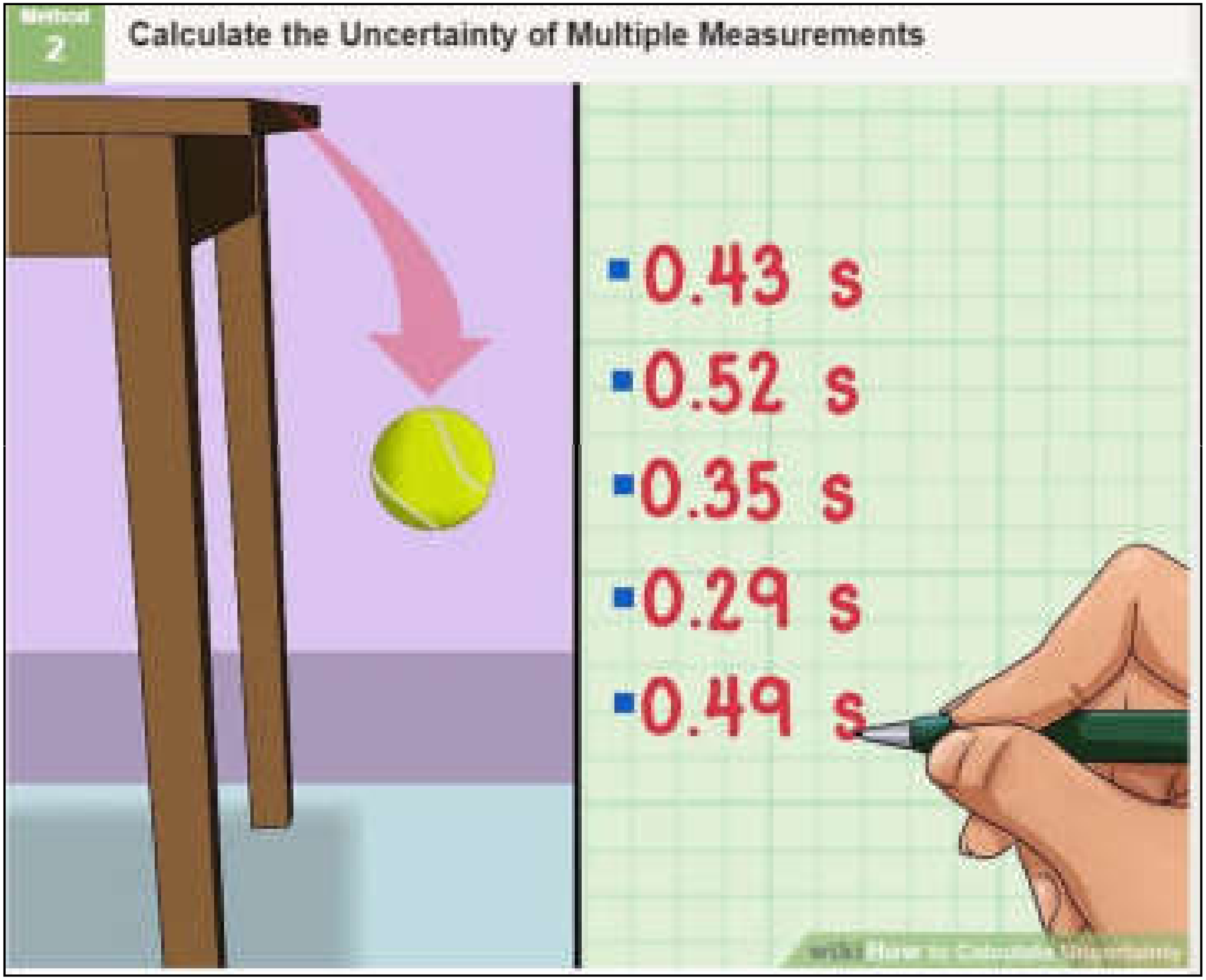
- Uncertainty – Range of possible error
- Example: 13.76 g $\pm$ .01 g

Means the true value lies within range

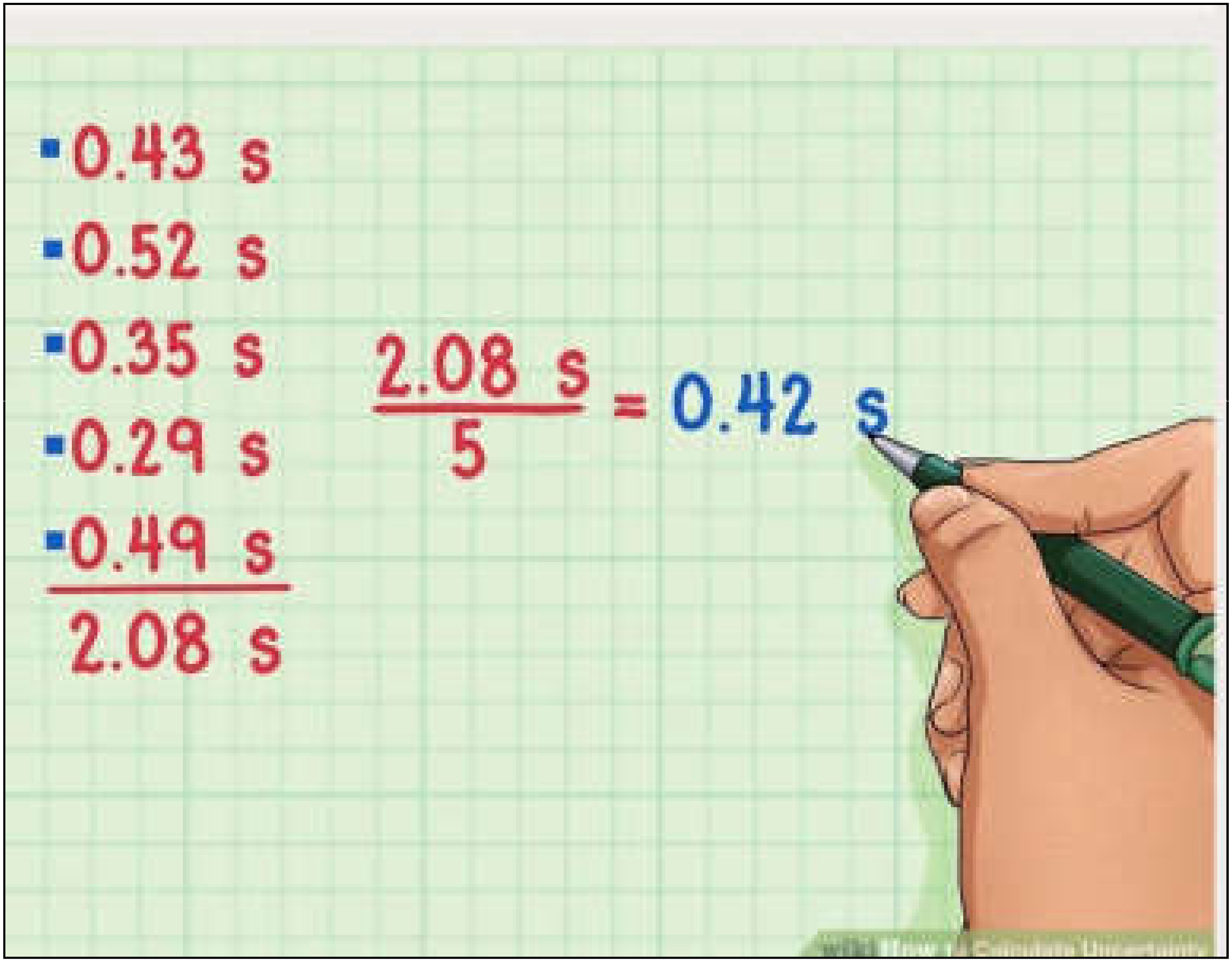
13.75 g
13.76 g
13.77 g

Example: a **measurement** of 5.07 g ± 0.02 g means that the experimenter is confident that the actual value for the quantity being **measured** lies between 5.05 g and 5.09 g. The **uncertainty** is the experimenter's best estimate of how far an experimental quantity might be from the "true value."

UNCERTAINTY CALCULATIONS



UNCERTAINTY CALCULATIONS



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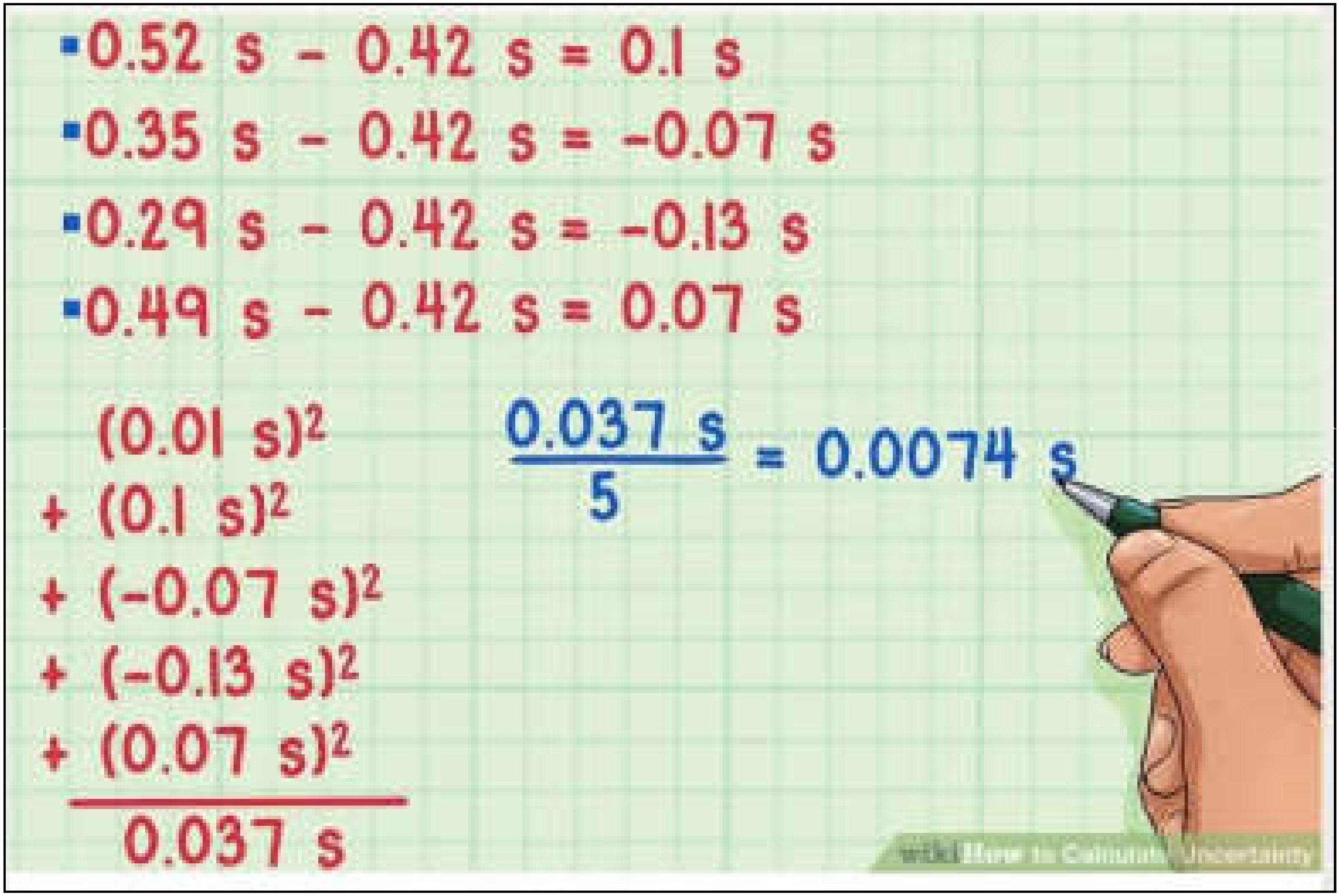
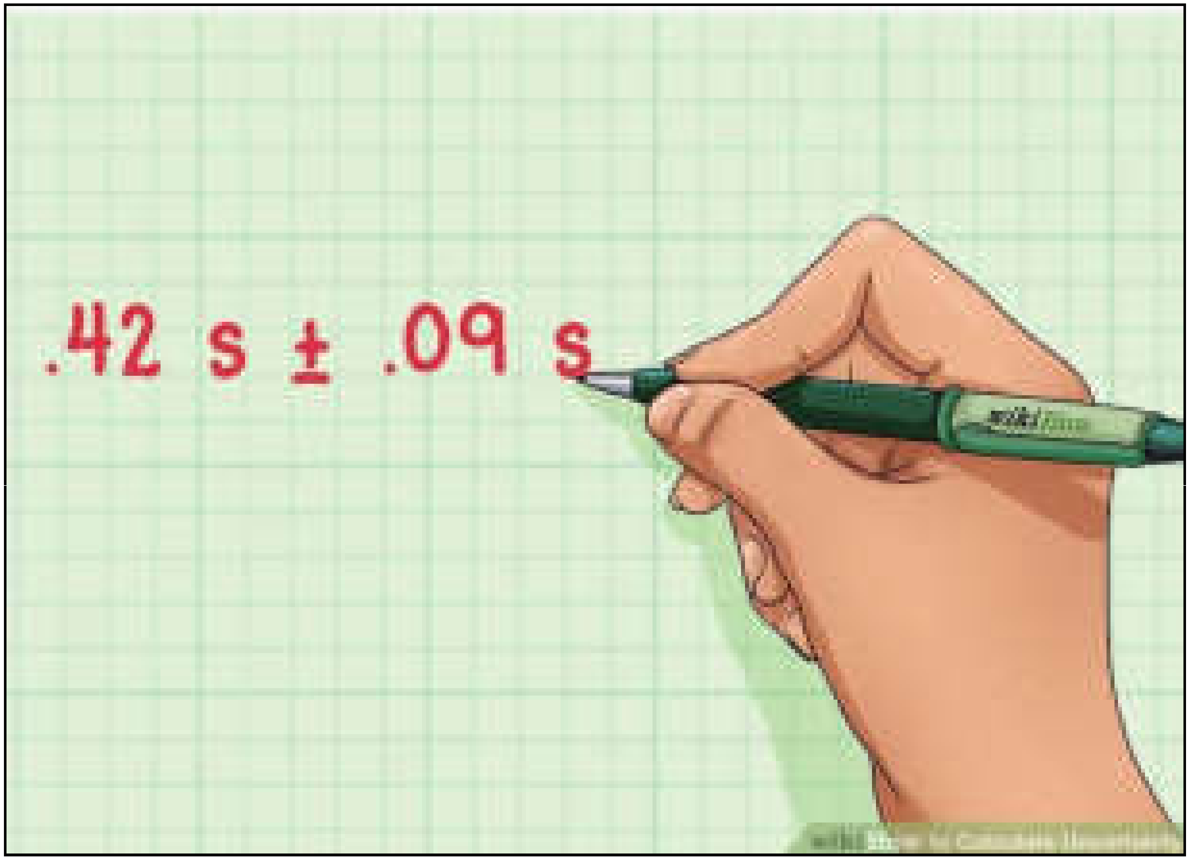


UNCERTAINTY CALCULATIONS



Mean Value +- Standard Deviation

ACCURACY

A pressure gauge with a measurement range of 0–10 bar has a quoted inaccuracy of ±1.0% of the full-scale reading.

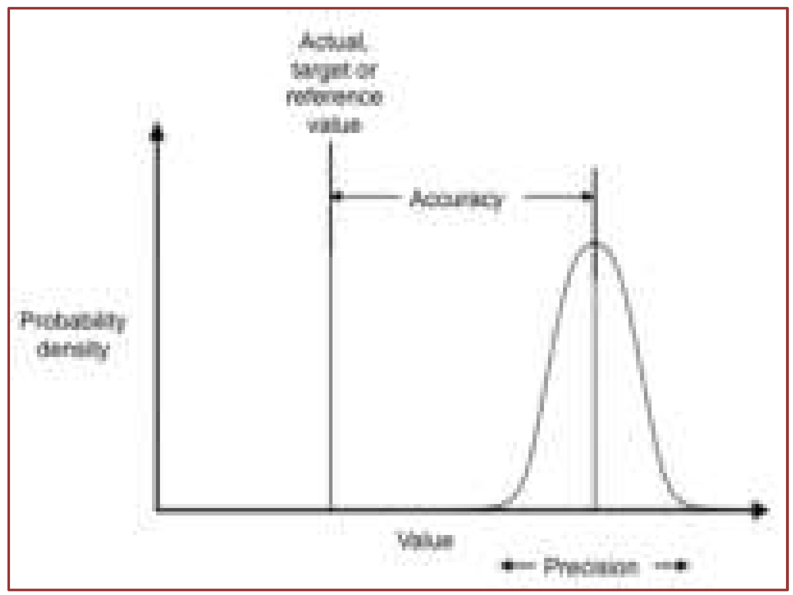
(a) What is the maximum measurement error expected for this instrument?
(b) What is the likely measurement error expressed as a percentage of the output reading if this pressure gauge is measuring a pressure of 1 bar?

Solution

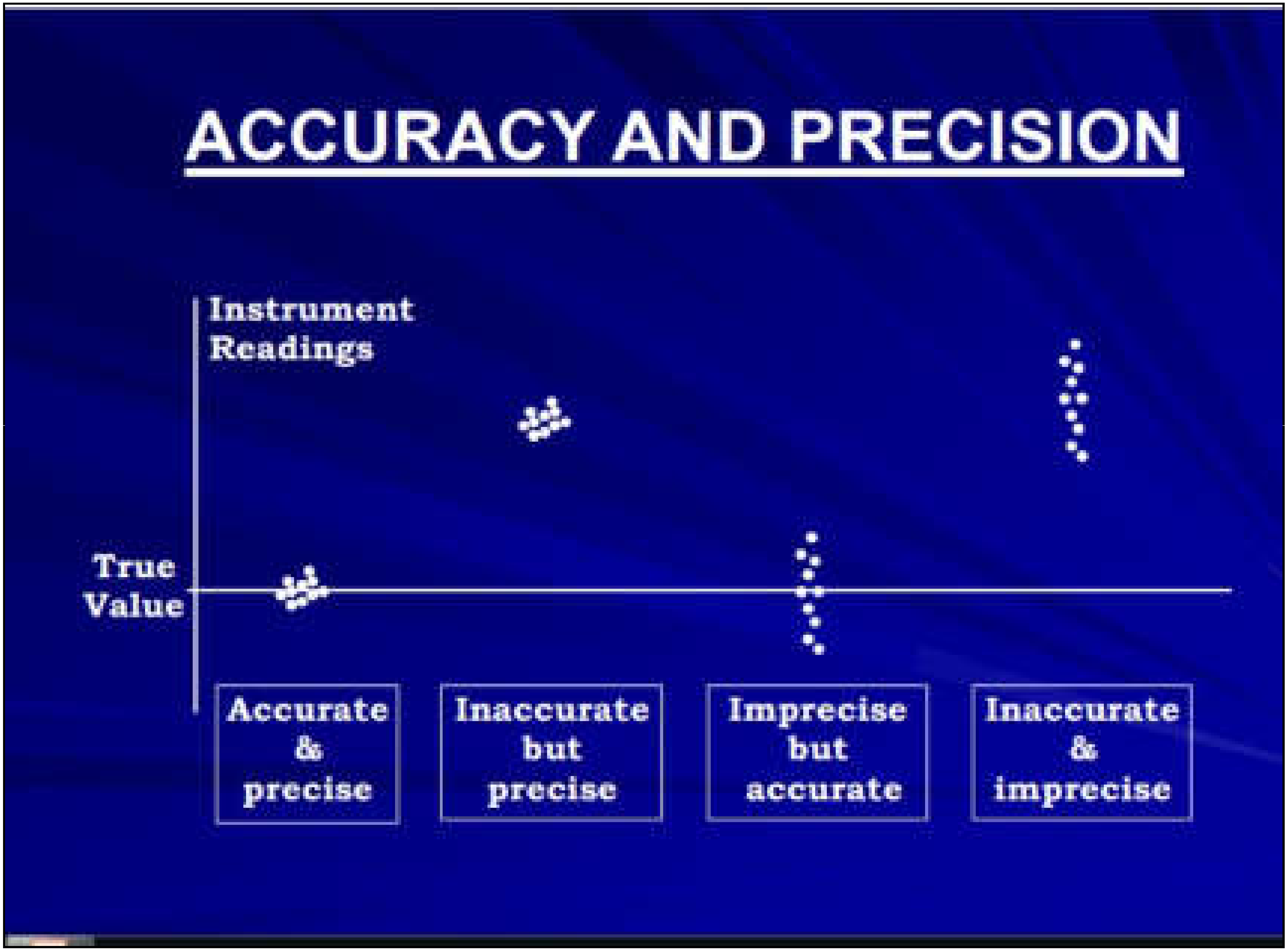
(a) The maximum error expected in any measurement reading is 1.0% of the full-scale reading, which is 10 bar for this particular instrument. Hence, the maximum likely error is 1.0% × 10 bar = 0.1 bar.
(b) The maximum measurement error is a constant value related to the full-scale reading of the instrument, irrespective of the magnitude of the quantity that the instrument is actually measuring. In this case, as worked out above, the magnitude of the error is 0.1 bar. Thus, when measuring a pressure of 1 bar, the maximum possible error of 0.1 bar is 10% of the measurement value.

PRECISION

- Precision is a term that describes an instrument's degree of freedom from errors . If a large number of readings are taken of the same quantity by a high-precision instrument, then the spread of readings will be very small
- Accuracy can be improved by calibration but not precision
- If you weigh a given substance five times, and get 3.2 kg each time, then your **measurement** is very **precise**. **Precision** is independent of accuracy. You can be very **precise** but inaccurate



ACCURACY and PRECISION



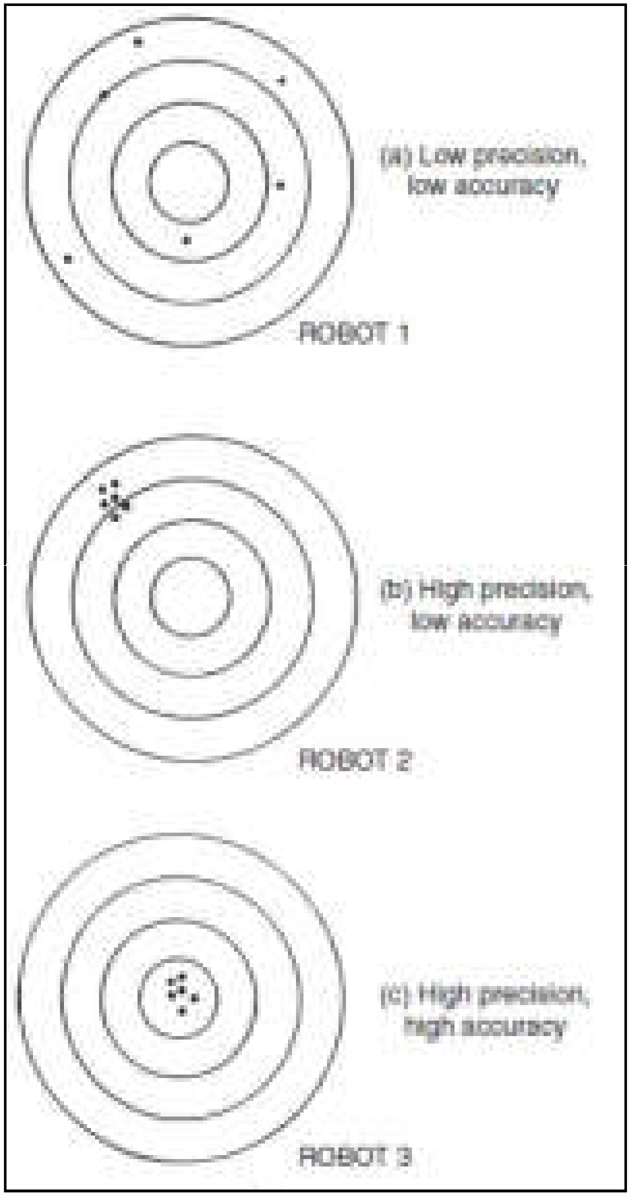
ACCURACY vs. PRECISION

The figure shows the results of tests on three industrial robots that were programmed to place components at a particular point on a table.

The target point was at the center of the concentric circles shown, and the black dots represent the points where each robot actually deposited components at each attempt. Both the accuracy and precision of Robot 1 is shown to be low in this trial.

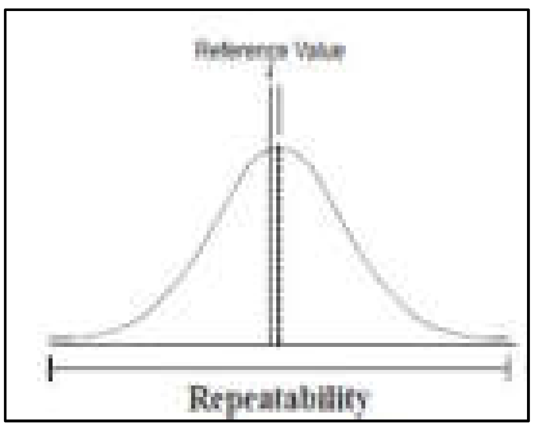
Robot 2 consistently puts the component down at approximately the same place but this is the wrong point. Therefore, it has high precision but low accuracy.

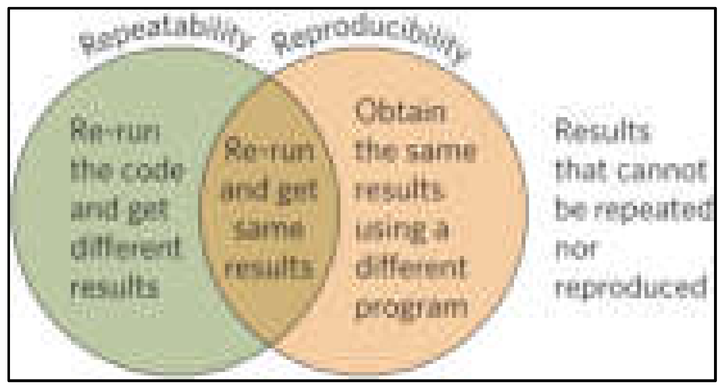
Finally, Robot 3 has both high precision and high accuracy, because it consistently places the component at the correct target position



REPEATABILITY and REPRODUCIBILITY

- Repeatability and Reproducibility (R & R) Studies evaluate the precision of a measurement system. It is important that the instrument properly calibrated before starting R & R study
- Repeatability describes the closeness of output readings when the same input is applied repetitively over a short period of time, with the same measurement conditions, same instrument and observer, same location, and same conditions of use maintained throughout
- Reproducibility describes the closeness of output readings for the same input when there are changes in the method of measurement, observer, measuring instrument, location, conditions of use, and time of measurement





REPEATABILITY and REPRODUCIBILITY

The width of a room is measured 10 times by an ultrasonic rule and the following measurements are obtained (units of meters): 5.381 5.379 5.378 5.382 5.380 5.383 5.379 5.377 5.380 5.381.

The width of the same room is then measured by a calibrated steel tape that gives a reading of 5.374 m, which can be taken as the correct value for the width of the room.

(a) What is the measurement precision of the ultrasonic rule?
(b) What is the maximum measurement inaccuracy of the ultrasonic rule?

Solution

(a) The mean (average) value of the 10 measurements made with the ultrasonic rule is 5.380 m.

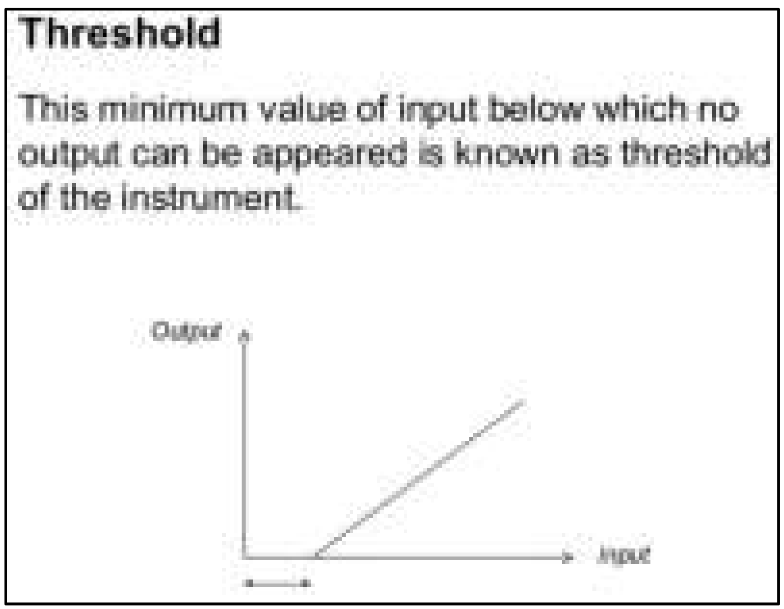
The maximum deviation below this mean value is −0.003 m and the maximum deviation above the mean value is +0.003 m. Thus the precision of the ultrasonic rule can be expressed as ±0.003 m (±3 mm).

(b) The correct value of the room width has been measured as 5.374 m by the calibrated steel rule. All ultrasonic rule measurements are above this, with the largest value being 5.383 m. This last measurement is the one that exhibits the largest measurement error. This maximum measurement error can be

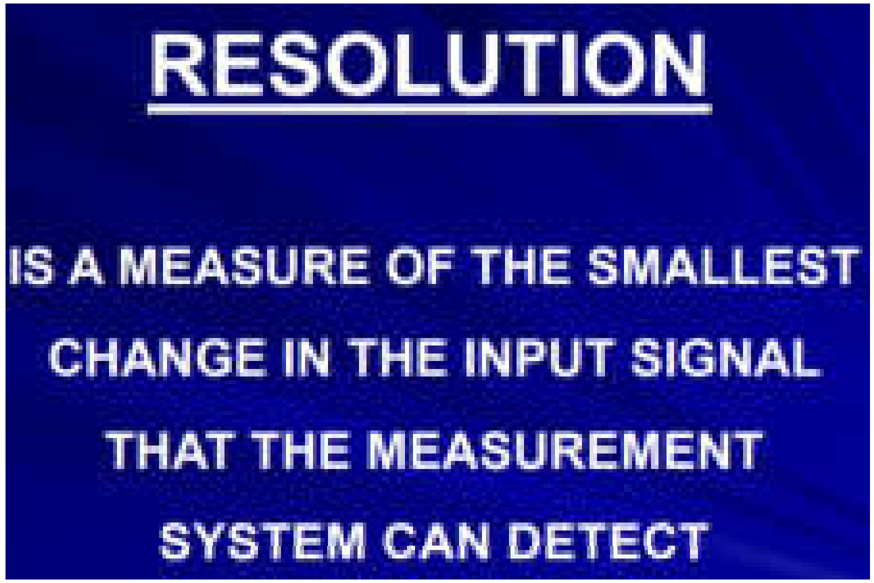
calculated as: 5.383 − 5.374 = 0.009 m (9 mm). Thus the maximum measurement inaccuracy can be expressed as +9 mm.

THRESHOLD

- If the input to an instrument is gradually increased from zero, the input will have to reach a certain minimum level before the change in the instrument's output reading. This minimum level of input is known as the threshold of the instrument. Example: Eddy current Speedometer used in automobiles typically have a threshold of about 15km/h



RESOLUTION



- Using a car speedometer as an example again, this has subdivisions of typically 10 miles/h. This means that when the needle is between the scale markings, we cannot estimate speed more accurately than to the nearest 5 miles/h. This value of 5 miles/h thus represents the resolution of the instrument.

SENSITIVITY

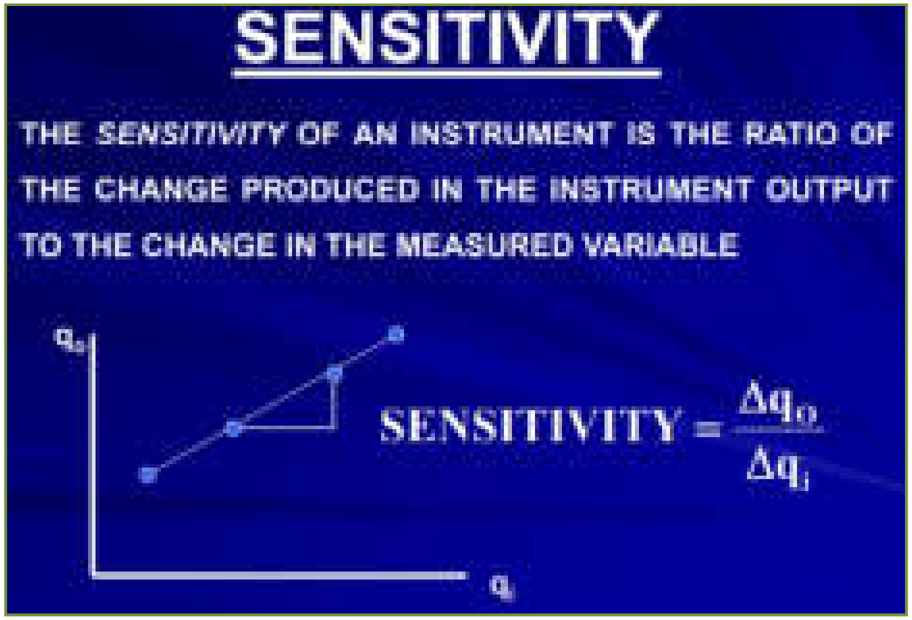
- Sensitivity is the smallest amount of difference in quantity that will change an instrument's reading
- Sensitivity of a spring balance can be expressed as 25 mm/kg (say), indicating additional load of 1 kg will cause additional displacement of the spring by 25mm
- Sensitivity of an instrument may also vary with temperature or other external or Environmental factors. This is known as ***sensitivity drift***
- Suppose the sensitivity of the spring balance mentioned above is 25 mm/kg at 20 ^{o}C and 27 mm/kg at 30^{o}C. Then the sensitivity drift/^{o}C is 0.2 (mm/kg)/^{o}C
- In order to avoid such sensitivity drift, sophisticated instruments are either kept at controlled temperature, or suitable in-built temperature compensation schemes are provided inside the instrument

SENSITIVITY

- The sensitivity of measurement is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount Thus, sensitivity is the ratio:

$$\frac{\text{scale deflection}}{\text{value of measurand producing deflection}}$$

- For example, a pressure of 2 bar produces a deflection of 10 degrees in a pressure gauge, the sensitivity of the instrument is 5 degrees/bar (assuming that the deflection is zero with zero pressure applied)



SENSITIVITY

The following resistance values of a platinum resistance thermometer were measured at a range of temperatures. Determine the measurement sensitivity of the instrument in Ω/°C.

Resistance (Ω)	Temperature (°C)
307	200
314	230
321	260
328	290

If these values are plotted on a graph, the straight-line relationship between resistance change and temperature change is obvious.

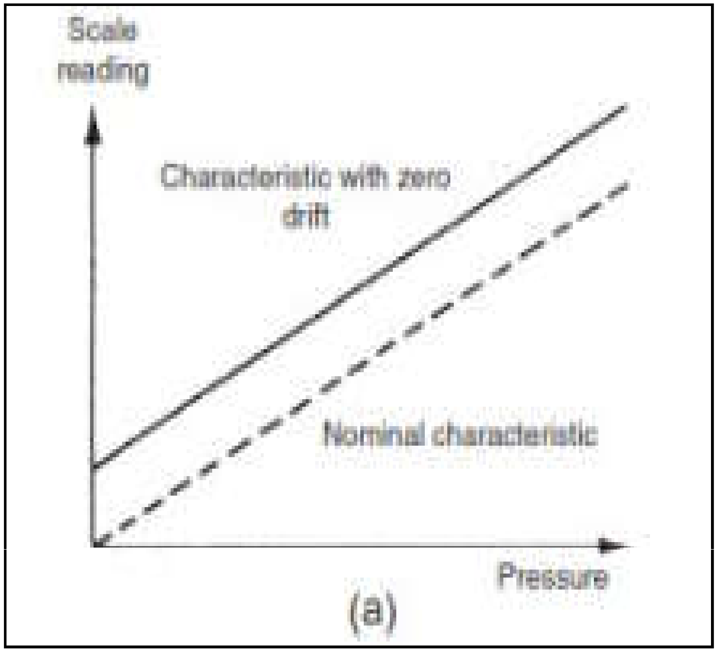
For a change in temperature of 30 °C, the change in resistance is 7 Ω. Hence the measurement sensitivity = 7/30 = 0.233 Ω/°C.

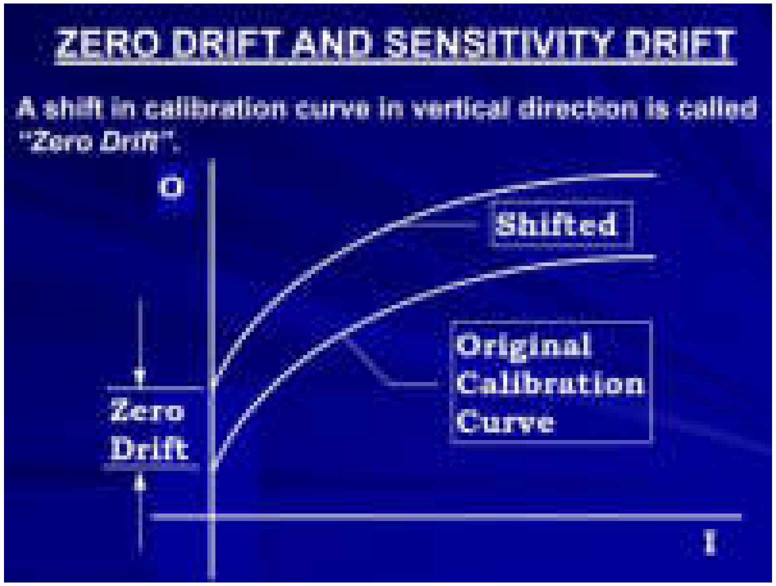
SENSITIVITY TO DISTURBANCE

- All calibrations and specifications of an instrument are only valid under controlled conditions of temperature, pressure, etc
- These standard ambient conditions are usually defined in the instrument specification
- As variations occur in the ambient temperature, etc., certain static instrument characteristics change, and the **sensitivity to disturbance** is a measure of the magnitude of this change. Such environmental changes affect instruments in two main ways, known as **zero drift and sensitivity drift**
- Zero drift is sometimes known by the alternative term, **bias**
- Sensitivity drift also called as **span**
- **Drift:** Environmental Effect to the instruments

ZERO DRIFT OR BIAS

- It describes the effect where the zero reading of an instrument is modified by a change in ambient conditions. This causes a constant error (System error) that exists over the full range of measurement of the instrument. The mechanical form of bathroom scale is a common example of an instrument that is prone to zero drift. It is quite usual to find that there is a reading of perhaps 1 kg with no one stood on the scale
- If someone of known weight 70 kg were to get on the scale, the reading would be 71 kg, and if someone of known weight 100 kg were to get on the scale, the reading would be 101 kg.
- Zero drift is normally removable by calibration. In the case of the bathroom scale just described, a thumbwheel is usually provided that can be turned until the reading is zero with the scales unloaded, thus removing the zero drift





ZERO DRIFT OR BIAS

The following table shows the output measurements of a voltmeter under two sets of conditions:

(a) Use in an environment kept of 20 °C, which is the temperature that it was calibrated at and

(b) Use in an environment at a temperature 50 °C.

Voltage Readings at Calibration Temperature of 20 °C (Assumed Correct)	Voltage Readings at Temperature of 50 °C
10.2	10.5
20.3	20.6
30.7	40.0
40.8	50.1

Determine the zero drift when it is used in the 50 °C environment, assuming that the measurement values when it was used in the 20 °C environment are correct. Also calculate the zero drift coefficient.

Solution

The zero drift at the temperature of 50 °C is the constant difference between the pairs of output readings, i.e., 0.3 V.

The zero drift coefficient is the magnitude of drift (0.3 V) divided by the magnitude of the temperature change causing the drift (30 °C). Thus the zero drift coefficient is 0.3/30 = 0.01 V/°C.

ZERO DRIFT OR BIAS

A spring balance is calibrated in an environment at a temperature of 20 °C and has the following deflection/load characteristic.

Load (kg)	0	1	2	3
Deflection (degrees)	0	20	40	60

It is then used in an environment at a temperature of 30 °C and the following deflection/load characteristic is measured.

Load (kg)	0	1	2	3
Deflection (degrees)	5	27	49	71

Determine the zero drift and sensitivity drift per °C change in ambient temperature.

At 20 °C, deflection/load characteristic is a straight line. Sensitivity = 20 degrees/kg.

At 30 °C, deflection/load characteristic is still a straight line. Sensitivity = 22 degrees/kg.

Zero drift (bias) = 5 degrees (the no-load deflection).

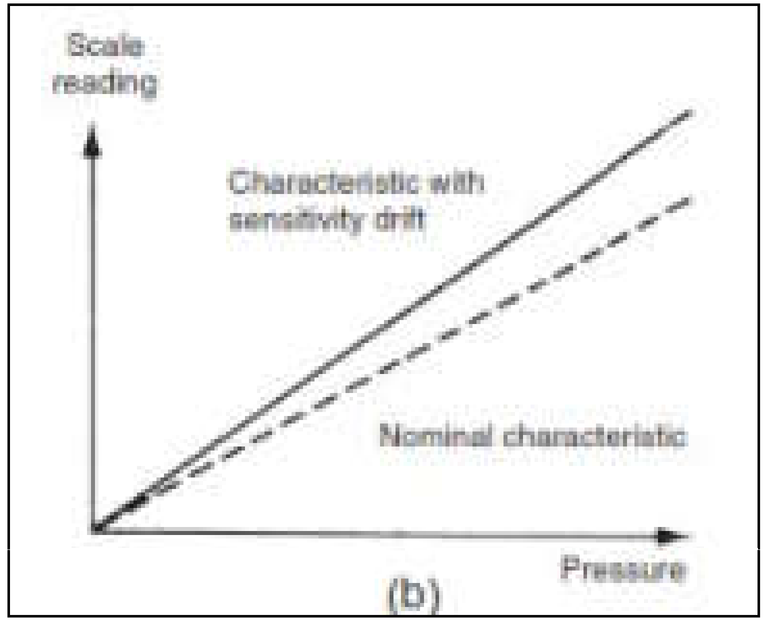
Sensitivity drift = 2 degrees/kg.

Zero drift/°C = 5/10 = 0.5 degrees/°C.

Sensitivity drift/°C = 2/10 = 0.2 (degrees per kg)/°C.

SENSITIVITY DRIFT

- It defines the amount by which an instrument's sensitivity of measurement varies as ambient conditions change
- It is quantified by sensitivity drift coefficients that define how much drift there is for a unit change in each environmental parameter that the instrument characteristics are sensitive to
- Many components within an instrument are affected by environmental fluctuations, such as temperature changes: for instance, the modulus of elasticity of a spring is temperature dependent
- Figure (b) shows what effect sensitivity drift can have on the output characteristic of an instrument



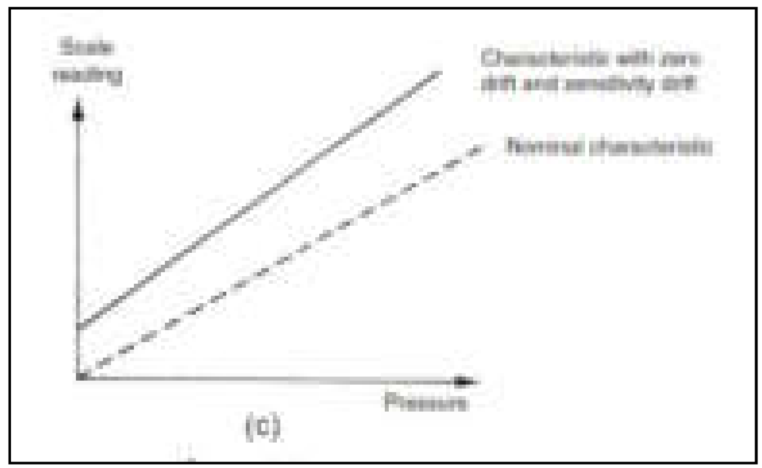
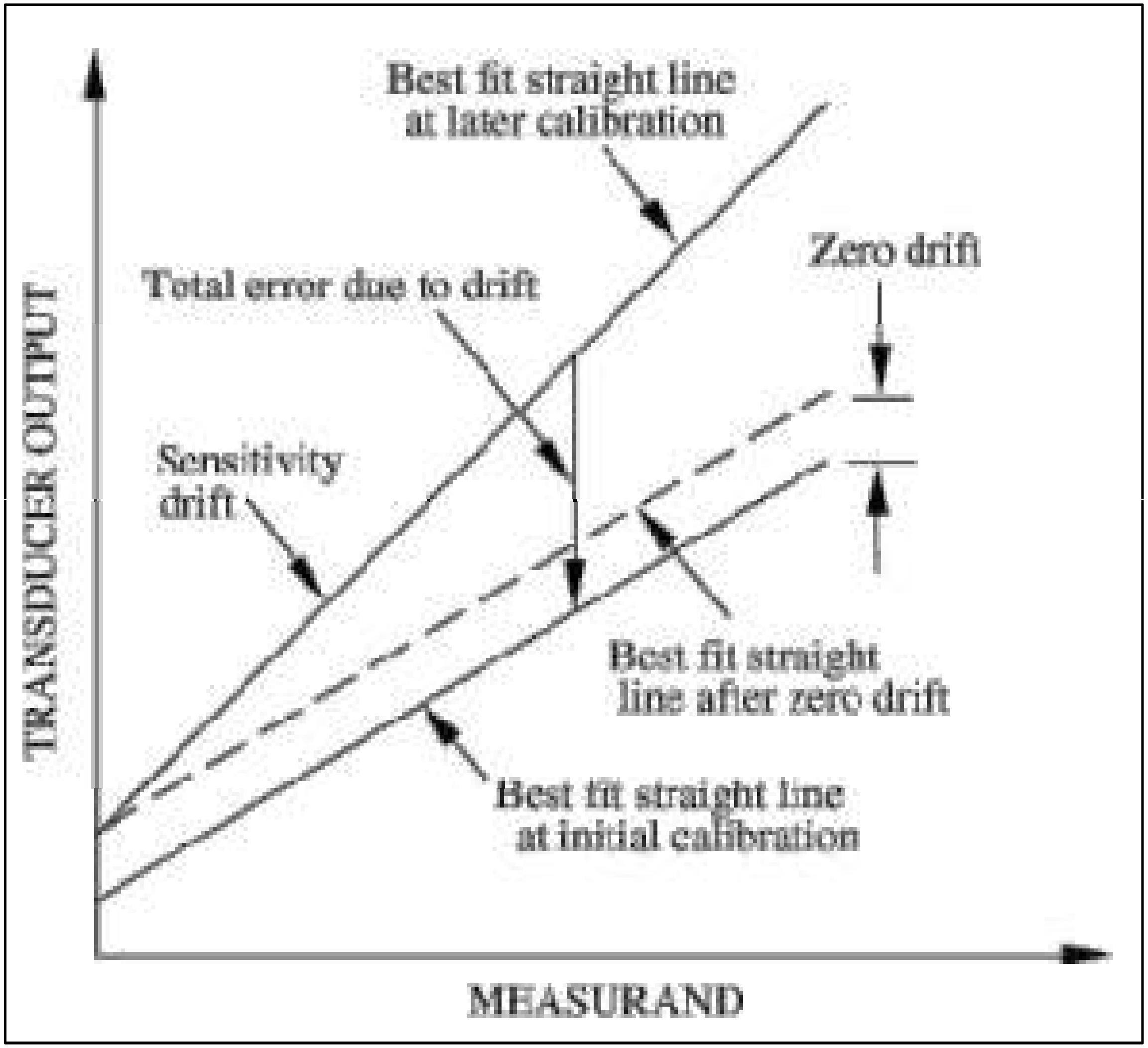


Fig (c): zero drift plus sensitivity drift

ZERO and SENSITIVITY DRIFT

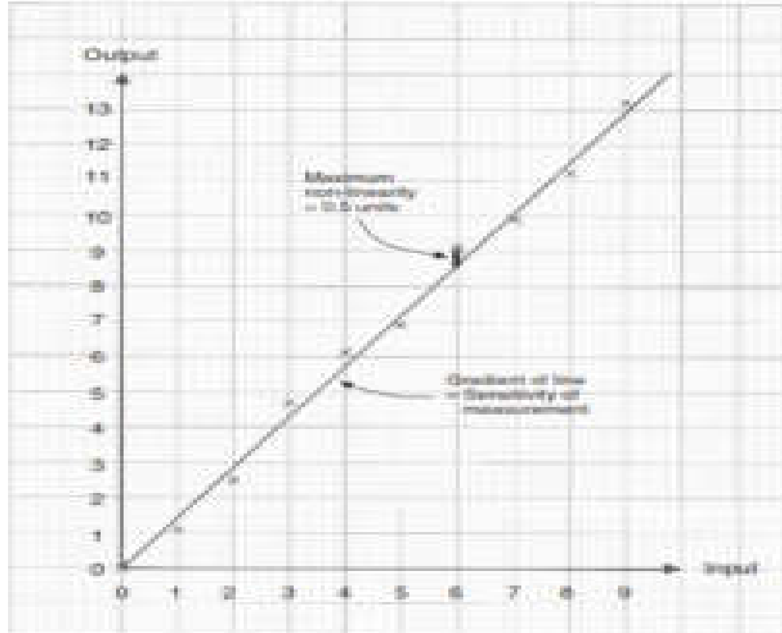


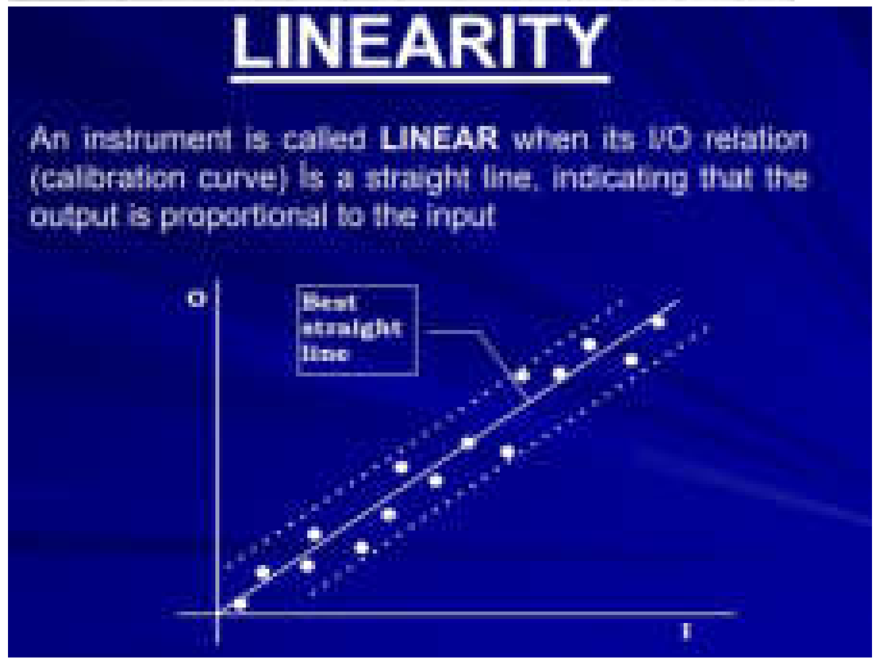
LINEARITY

- Linearity is defined as the ability of an instrument to reproduce its input linearly
- Linearity is simply a measure of the maximum deviation of the calibration points from the ideal straight line
- Linearity is defined as,

Maximum deviation of output from idealized straight line/Actual readings

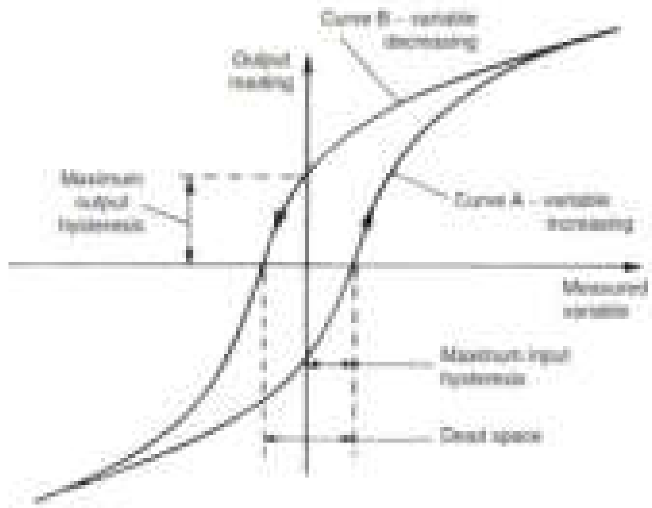
- The X's marked on Figure show a plot of the typical output readings of an instrument when a sequence of input quantities are applied to it
- The nonlinearity is then defined as the maximum deviation of any of the output readings marked X from this straight line. Nonlinearity is usually expressed as a percentage of full-scale reading

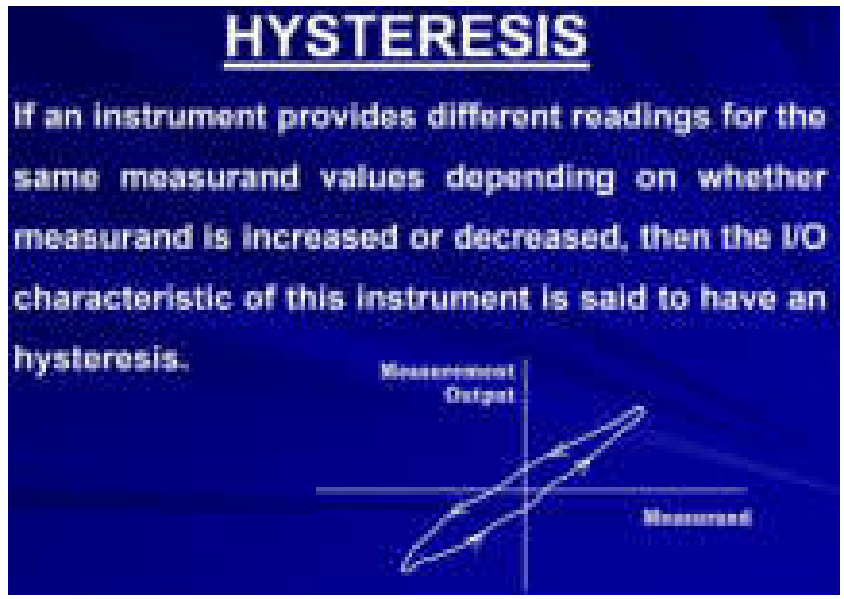




HYSTERESIS

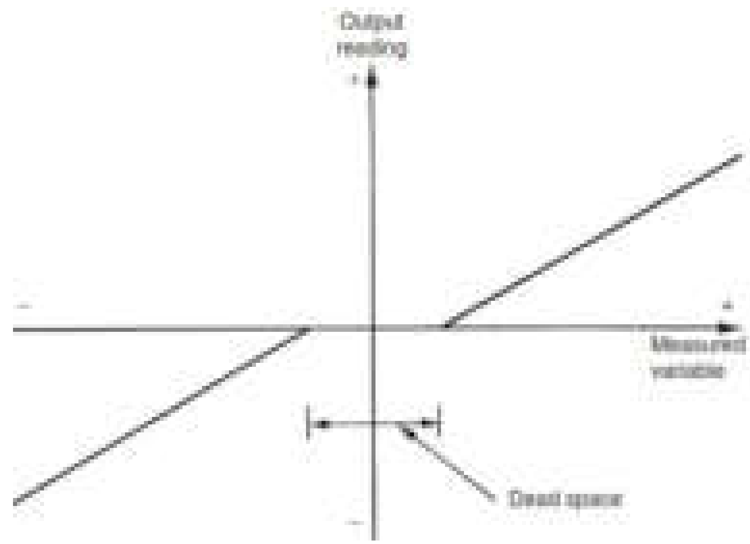
- Figure shows illustrates the output characteristic of an instrument that exhibits hysteresis. If the input measured quantity to the instrument is steadily increased from a negative value, the output reading varies in the manner shown in curve (A)
- If the input variable is then steadily decreased, the output varies in the manner shown in curve (B). The non coincidence between these loading and unloading curves is known as hysteresis
- Two quantities are defined, maximum input hysteresis and maximum output hysteresis, as shown Figure. Hysteresis is most commonly found in instruments that contain springs, such as the passive pressure gauge





DEAD SPACE/DEAD ZONE

- Dead space is defined as the range of different input values over which there is no change in output value.
- Some instruments that do not suffer from any significant hysteresis can still exhibit a dead space in their output characteristics however
- Backlash in gears is a typical cause of dead space, and results in the sort of instrument output characteristic shown in Figure.



Measurement
Of
Pressure

Instructional Objectives

Understands

- Different methods for measurement of pressure using elastic transducers
- Construction and working principle of
    - Diaphragms
    - Bellows
    - Bourdon Tube Pressure Gauges

Measurement of Gauge Pressure

- Mainly carried out by using elastic elements:
  - Diaphragms
  - Bellows
  - Bourdon tubes.
- **These elastic elements change their shape with applied pressure and the change of shape can be measured using suitable deflection transducers.**

Measurement of Gauge Pressure

Deflection Transducer

- This transducer uses an **elastic material to convert pressure to displacement e.g**. stainless steel, brass.
- The displacement will be proportionate to the value of pressure exerted.
- Suitable to be used in an automatic control system.
- The main element used is in the shape of Bourdon tube, bellow or diaphragm.
- The secondary element is the element that will **convert the displacement to electrical signals where the displacement can be detected through resistivity change, inductance or capacitance.**

Diaphragms

- Diaphragms may be of three types:

(based on the applied pressure and the corresponding displacements)

  - **Thin plate**
  - **Membrane**
  - **Corrugated diaphragm**

- Thin plate (fig. 1(a)) is made by machining a solid block and making a **circular cross sectional area with smaller thickness in the middle.**
- It is used for measurement of relatively higher pressure.

Diaphragms

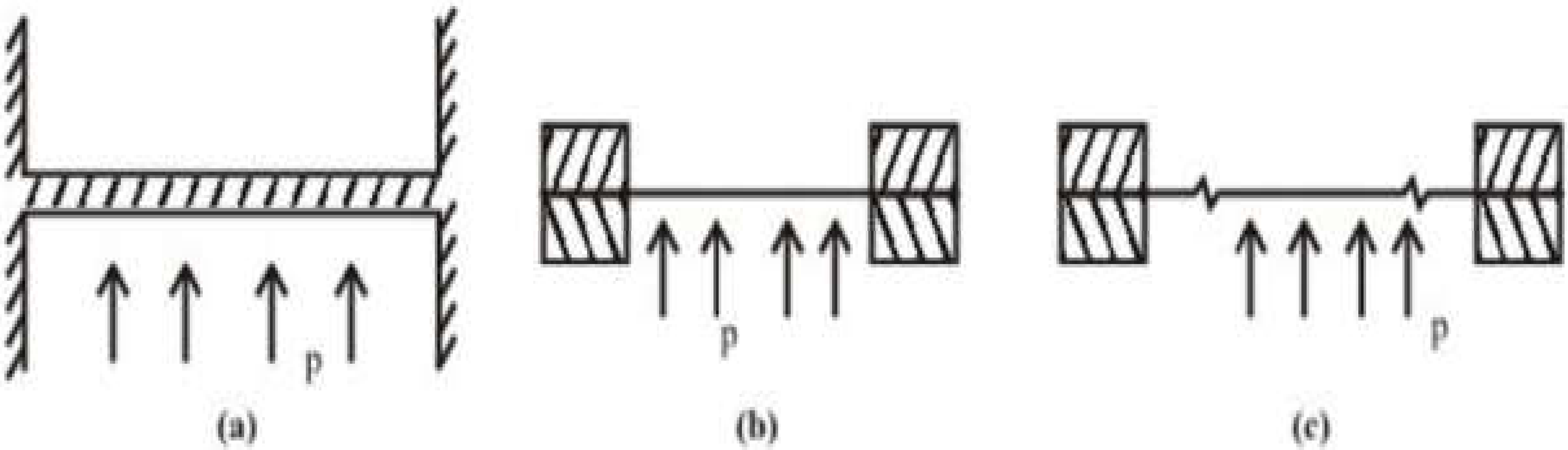
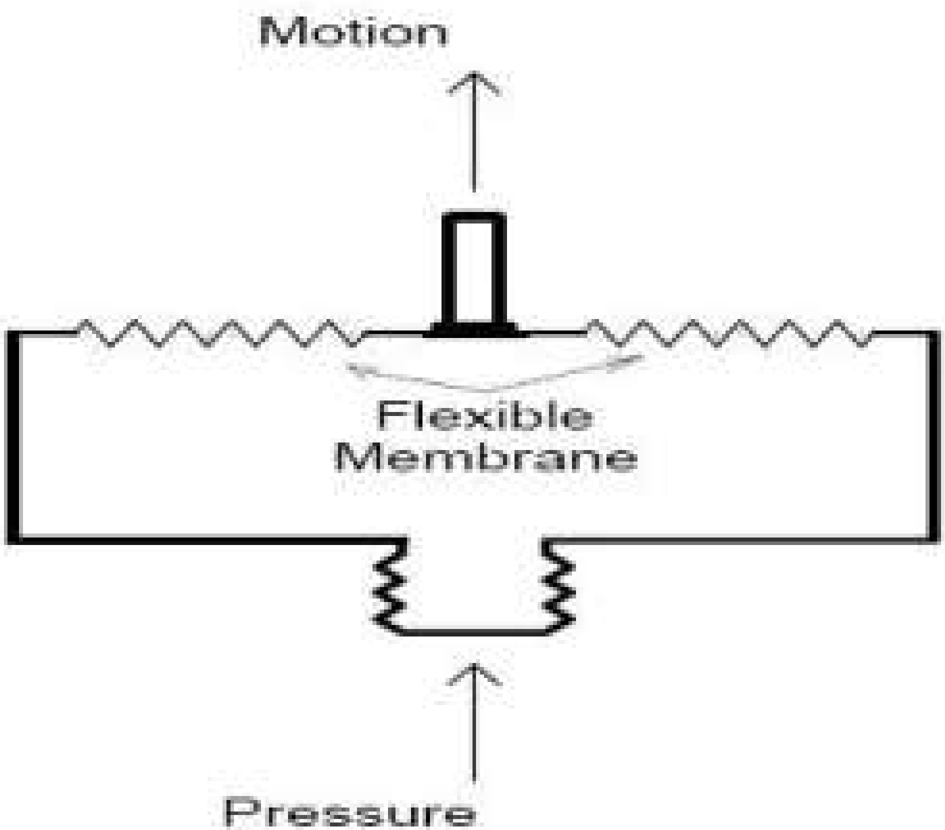


Fig. 1 (a) Thin plate, (b) Membrane and (c) Corrugated diaphragm.

Diaphragms



Diaphragms

- In a membrane the sensing section is glued in between two solid blocks as shown in fig. 1(b).
- The thickness is smaller; as a result, when pressure is applied on one side, the displacement is larger. Hence **increase in sensitivity** of the system.
- The sensitivity can be further enhanced in a **corrugated diaphragm** (fig. 1(c)), and a large deflection can be obtained for a small change in pressure; however **at the cost of linearity**.
- The materials used are **Bronze, Brass, and Stainless steel.**

Diaphragms

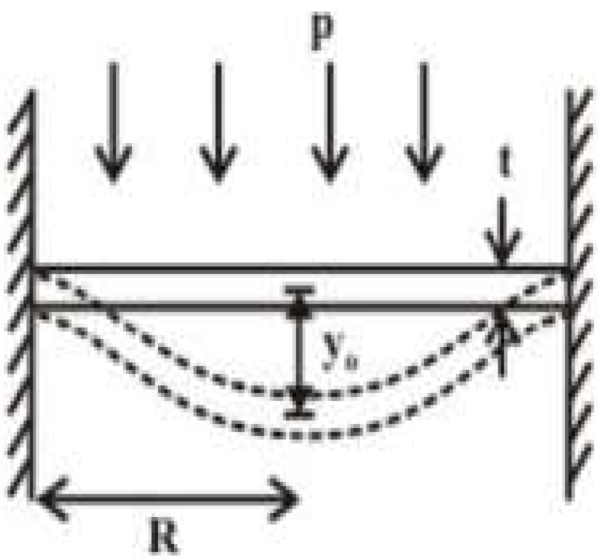


Fig. 2 Displacement of a diaphragm

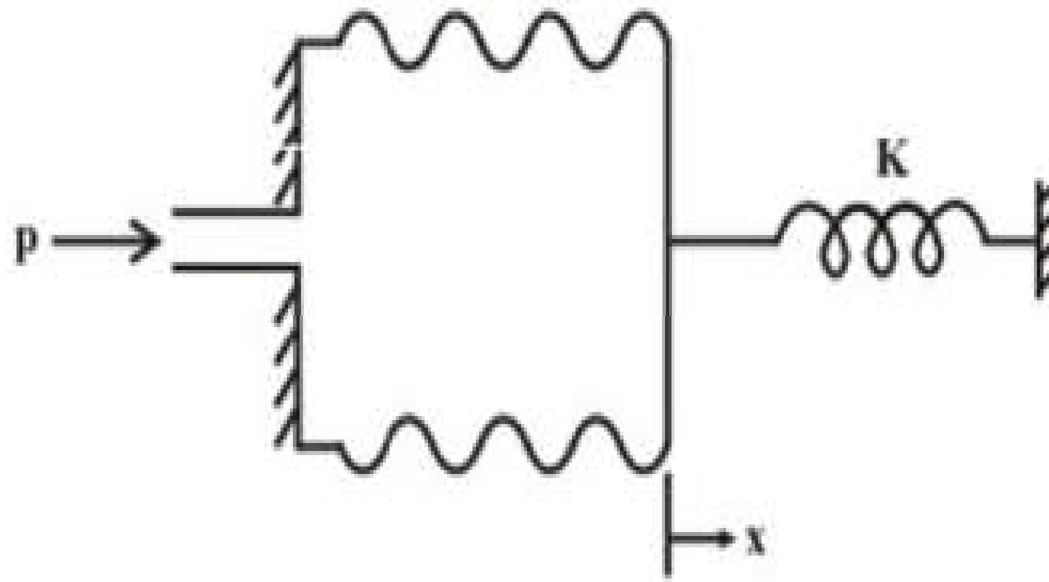


Fig. 3 Bellows

Diaphragms

When pressure is applied to a diaphragm, it deflates and the maximum deflection at the centre (y_0) can measured using a displacement transducer. For a Thin plate, the maximum deflection y_0 is small ($y_0 < 0.3t$) and referring fig. 2, a linear relationship between p and y_0 exists as:

$$y_0 = \frac{3}{16} p \frac{(1-\nu^2)}{Et^3} R^4$$

where, E = Modulus of elasticity of the diaphragm material, and

ν = Poisson's ratio.

However, the allowable pressure should be less than:

$$p_{max} = 1.5\left(\frac{t}{R}\right)^2 \sigma_{max}$$

where, σ_{max} is the safe allowable stress of the material.

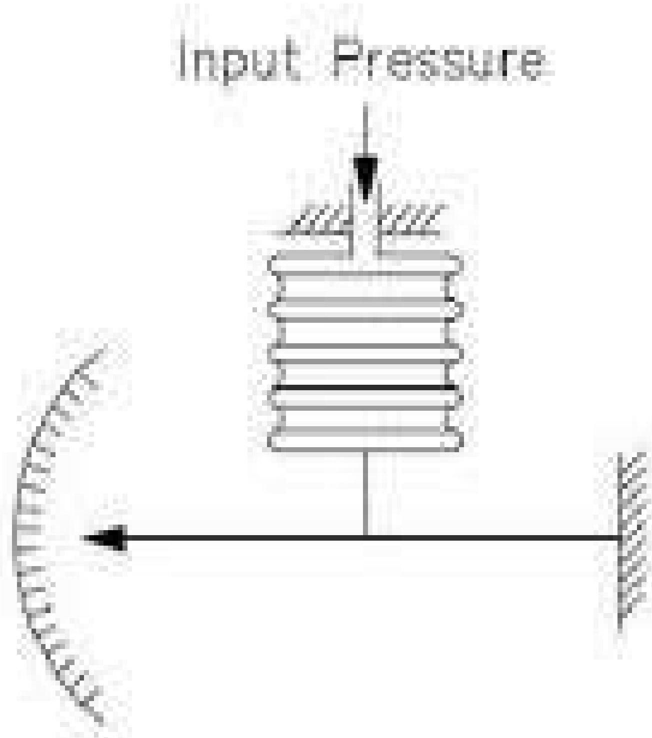
Diaphragms

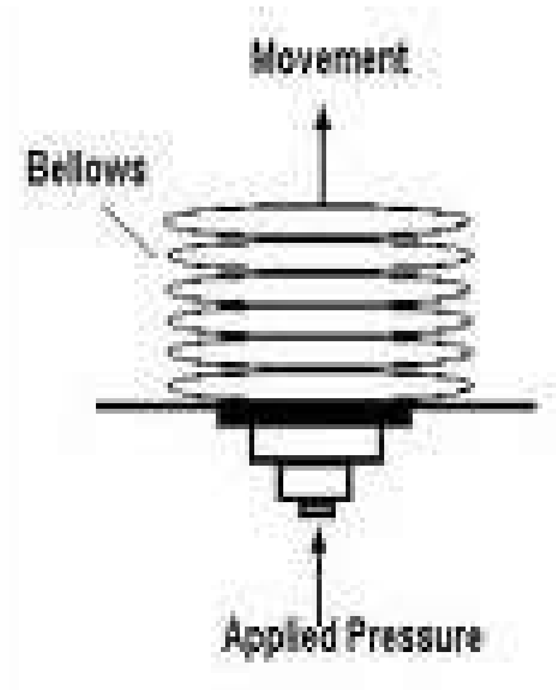
- For a corrugated diaphragm, it is difficult to give any definite mathematical relationship between p and y
- But the relationship is also **highly nonlinear.**

Bellows

- Bellows (fig. 3) are made with a number of convolutions from a soft material and **one end of it is fixed,** wherein air can go through a port. **The other end of the bellows is free to move.**
- The displacement of the free end increases with the number of convolutions used.
- Number of convolutions varies between 5 to 20.

Bellows





Bellows

- Often an external spring is used opposing the movement of the bellows; as a result a linear relationship can be obtained from the equation:

$$p.A = k.x$$

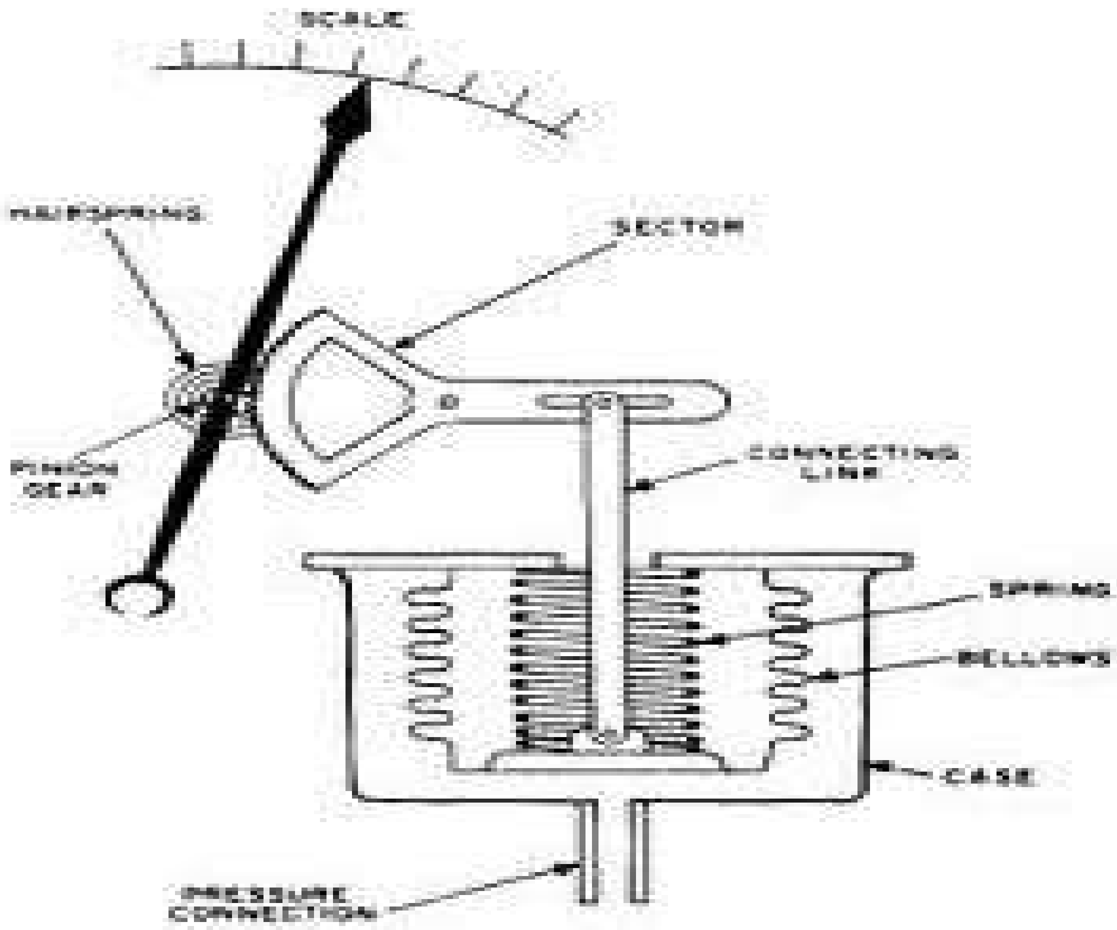
where, A is the area of the bellows

k is the spring constant and

x is the displacement of the bellows.

- **Phosphor Bronze, Brass, Beryllium Copper, Stainless Steel** are normally used as the materials for bellows.
- Bellows are manufactured either by (i) turning from a solid block of metal, or (ii) soldering or welding stamped annular rings, or (iii) rolling (pressing) a tube.

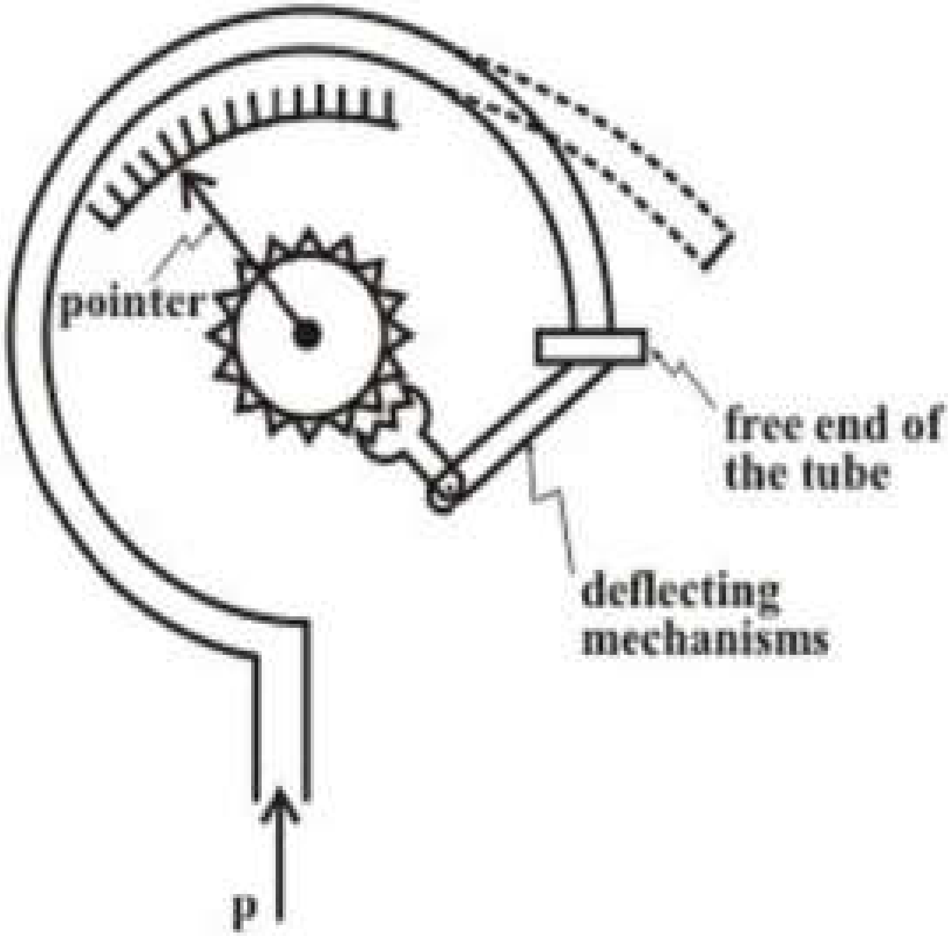
Bellows

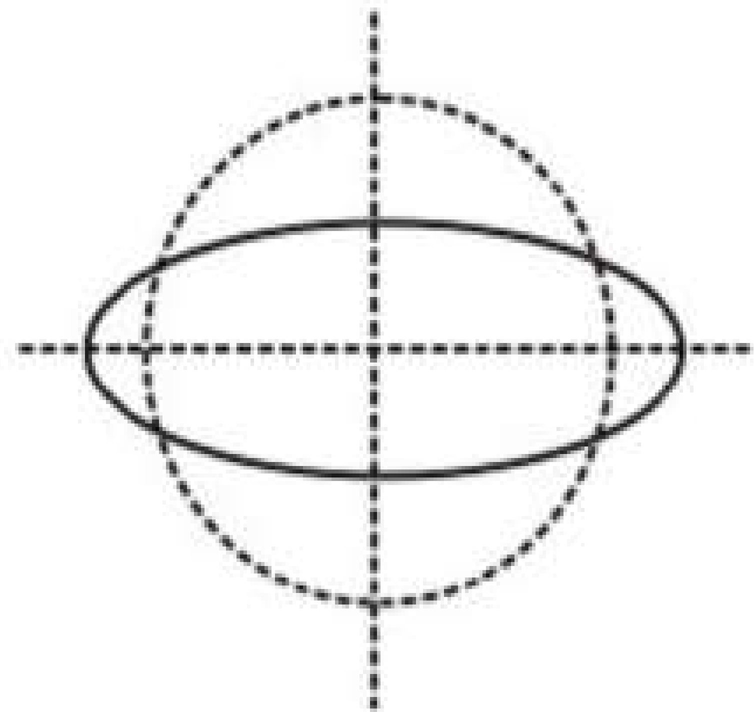


SCALE
HAIRSPRING
SECTOR
PINION
GEAR
CONNECTING
LINK
SPRING
BELLOWS
CASE
PRESSURE
CONNECTION

Bourdon Tube

- Bourdon tube pressure gages are extensively used for local indication.
- Bourdon tube pressure gages can be used to measure over a wide range of pressure: form vacuum to pressure as high as few thousand psi.
- It is basically consisted of a **C-shaped hollow tube, whose one end is fixed and connected to the pressure tapping, the other end free,** as shown in fig. 4.
- The cross section of the **tube is elliptical.**





Cross section of the tube

Fig. 4 Bourdon tube

Bourdon Tube

- When pressure is applied, the elliptical tube **tries to acquire a circular cross section;**
- As a result, stress is developed and the **tube tries to straighten up.**
- Thus the free end of the tube moves up, depending on magnitude of pressure.
- A deflecting and indicating mechanism is attached to the free end that rotates the pointer.
- The materials used are commonly Phosphor Bronze, Brass and Beryllium Copper.
- For a 2” overall diameter of the C-tube the useful travel of the free end is 1/8” approximately

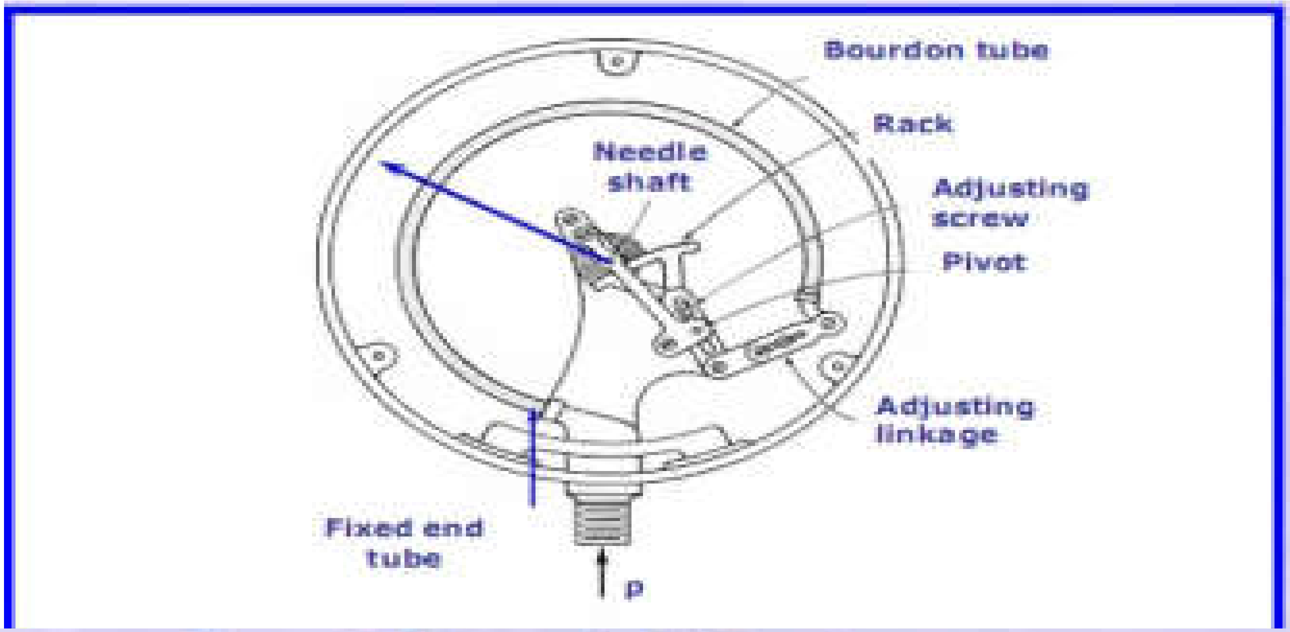


Figure 68 Schematic of a Bourdon pressure gage

Figure 69 Photograph of a Bourdon gage taken from the web
(Dr. Pravin Varma, Mount Allison University, Sackville, New Brunswick Canada)

Bourdon Tube

$$\Delta a = 0.05\,(a.p/E)\,(r/t)^{0.2}\,(x/y)^{0.33}(x/t)^{3}$$

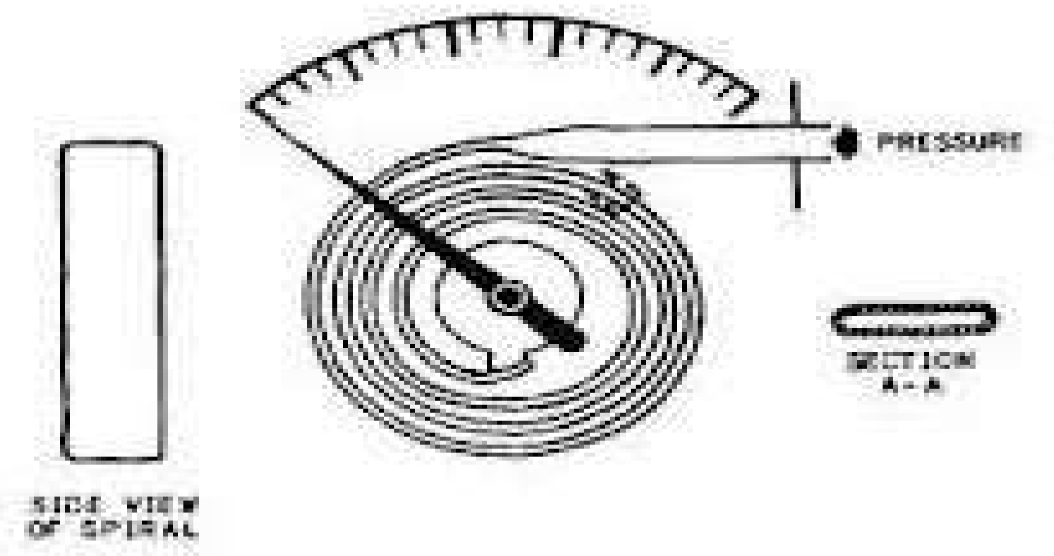
Δa- Displacement of tube tip
a-Length of tube
p- Intensity of pressure
t- Wall thickness of tube
x&y- Dimensions of tube
E- Modulus of elasticity

- **Displacement of tip varies**
  - **inversely to the wall thickness of the tube**
  - **Directly to the length of the arc**

- **Length of arc can be increased further by two ways**
  - **Spiral**
  - **Helix form**

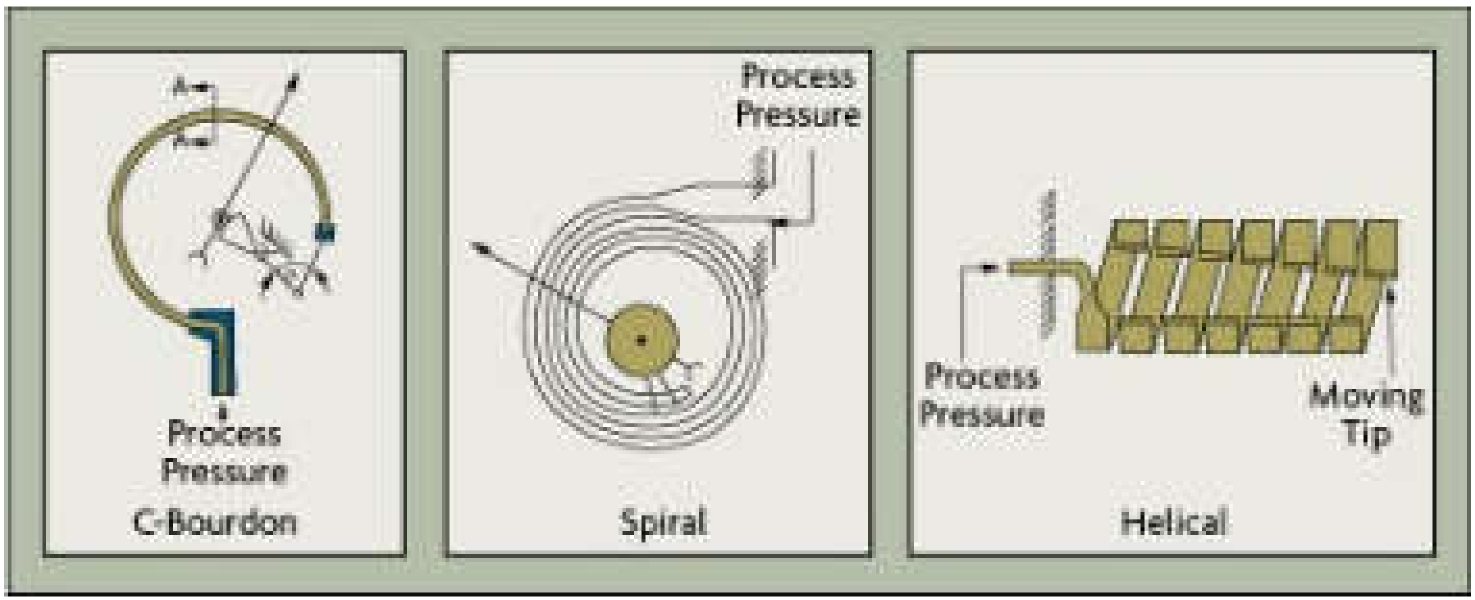
- Avoiding the need for further magnification by geared sector and pinion as in Bourdon tube pressure gauge

Spiral type pressure gauge



Basic forms of tubes used for pressure sensors

Though the C-type tubes are most common, other shapes of tubes, such as **helical, twisted or spiral tubes** are also in use.



Bourdon Tube

Advantage

- Simple in construction and design
- Available in several different ranges
- Capable to measure gauge, absolute and differential pressure
- Excellent sensitivity
- Easy calibration

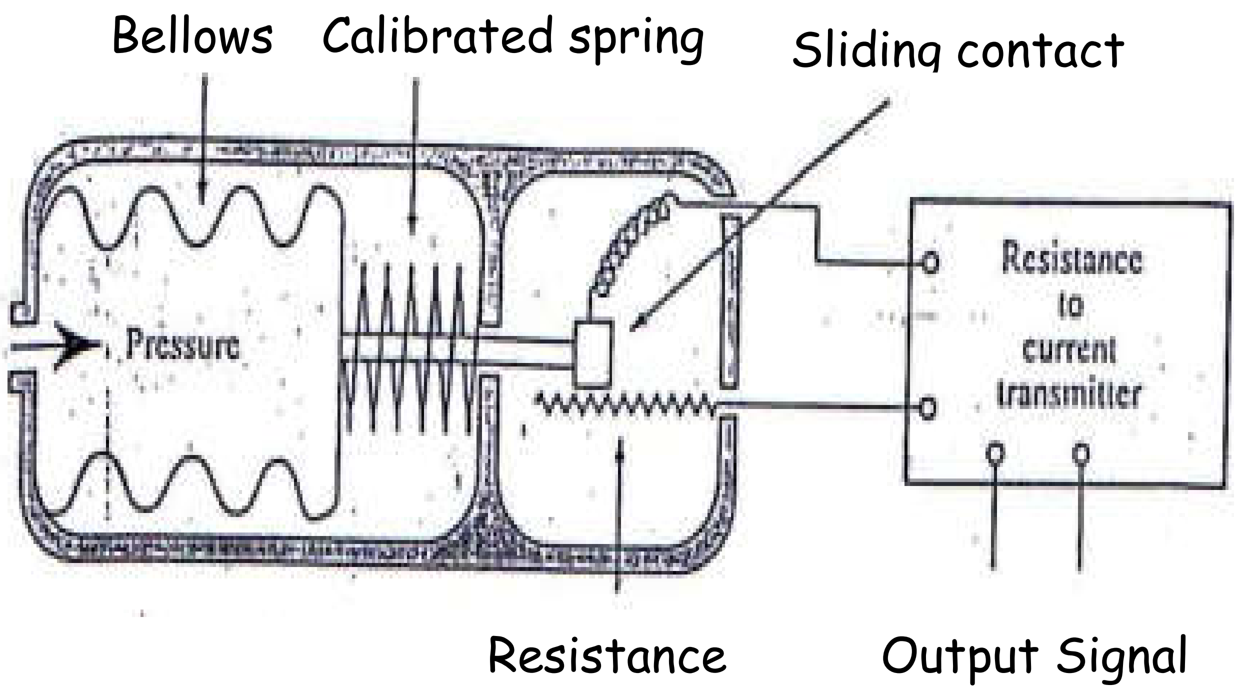
Disadvantages

- Susceptibility of shock and vibration
- Slow response to pressure changes
- Unsuitable for low pressure applications

Example 1 :

i. Bellow-resistance pressure sensor

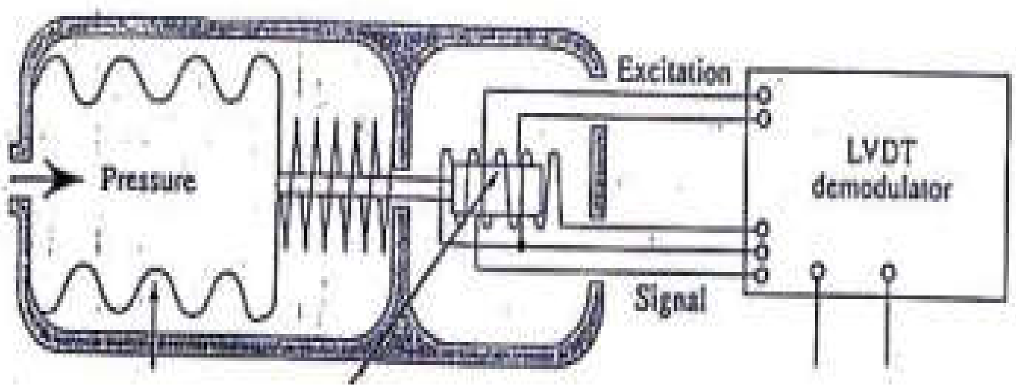
- **The pressure is proportionate to the resistivity.**
- **The resistance change is detected by displacement of sliding contact in the resistance element.**



Example 2:

ii. Bellow-inductance pressure sensor

- The pressure is proportionate to the inductance change which is detected from the displacement of the core in the wire coil.
- The core movement will produce AC signal output which will give the value and direction of inductance.
- LVDT (linear variable differential transformer) demodulator is used to convert the AC output to DC.

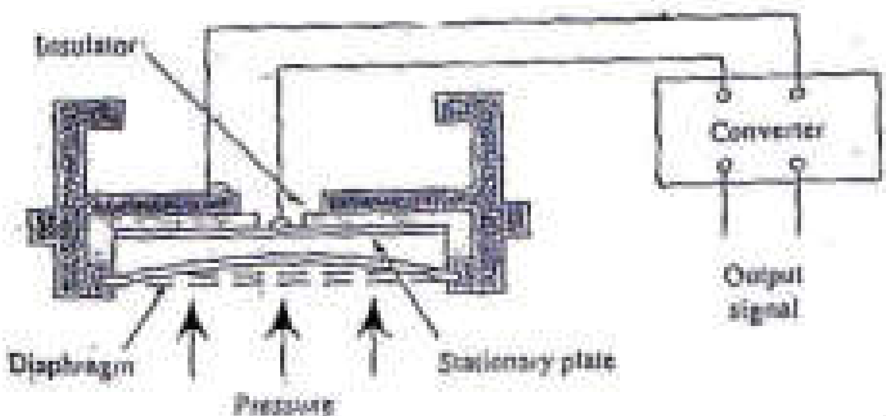


Bellows Core Output Signal

Example 3:

iii. Diaphragm-capacitance pressure sensor

- **The pressure is proportionate to the capacitance change at the output through dielectric change.**
- **Pressure from the sensor element causes the diaphragm to move towards the plate and produces dielectric change.**



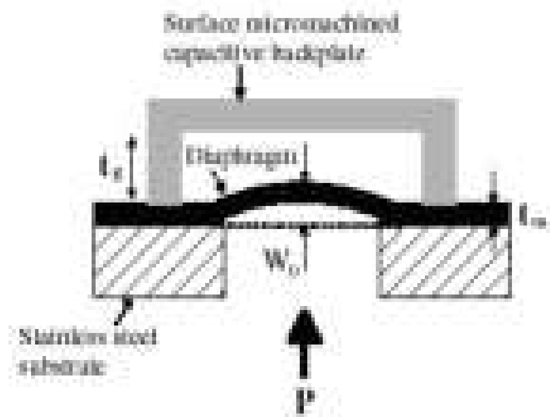
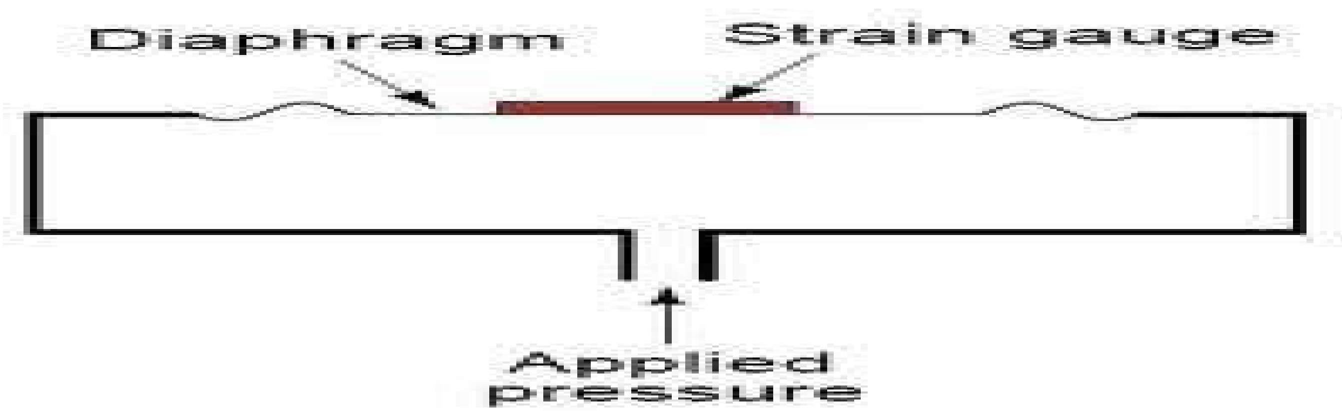


Figure 4. A schematic diagram of the side view of the capacitive pressure sensor.

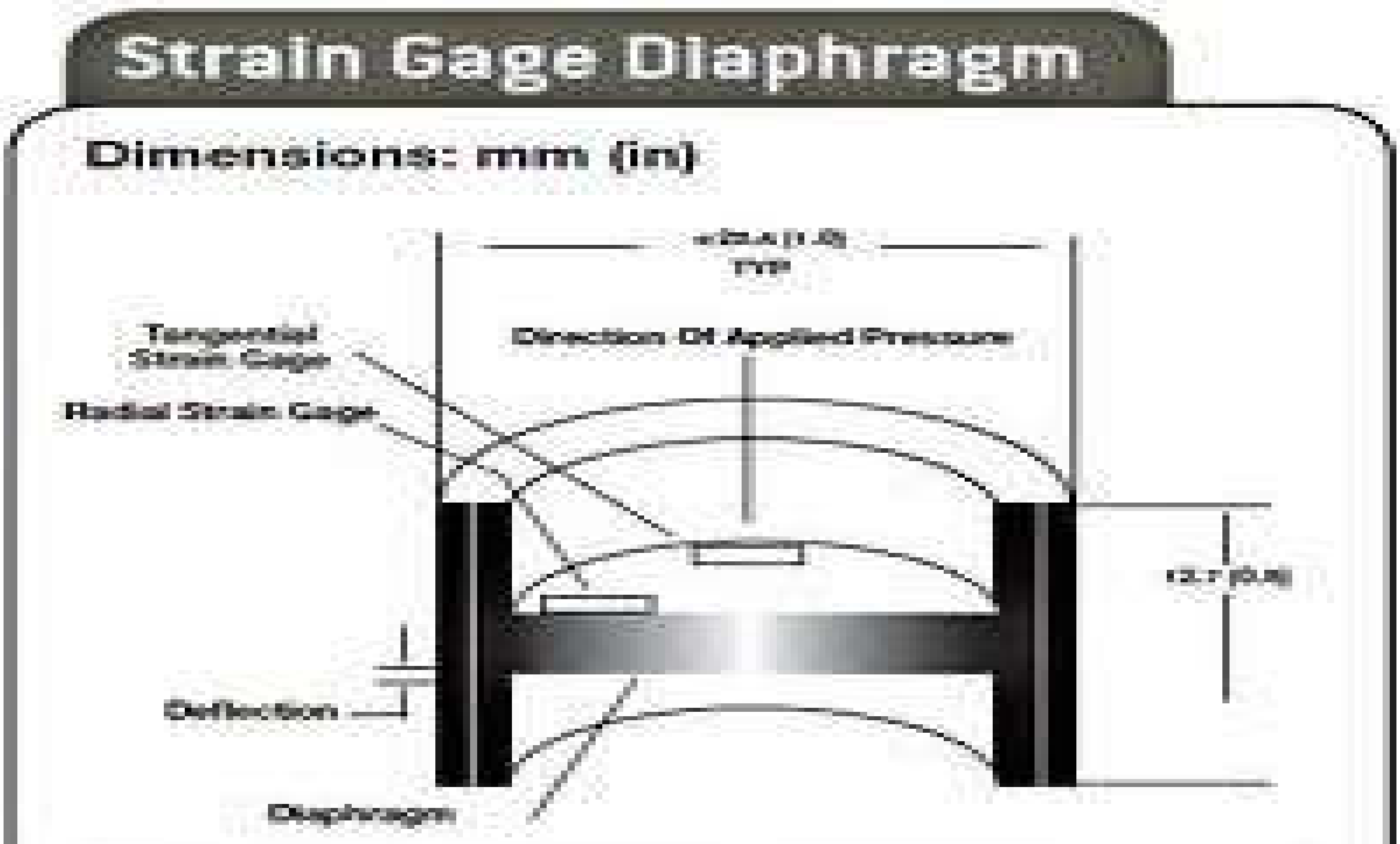
Example 4:

iv. Diaphragm-Strain gauge pressure sensor



Example 4:

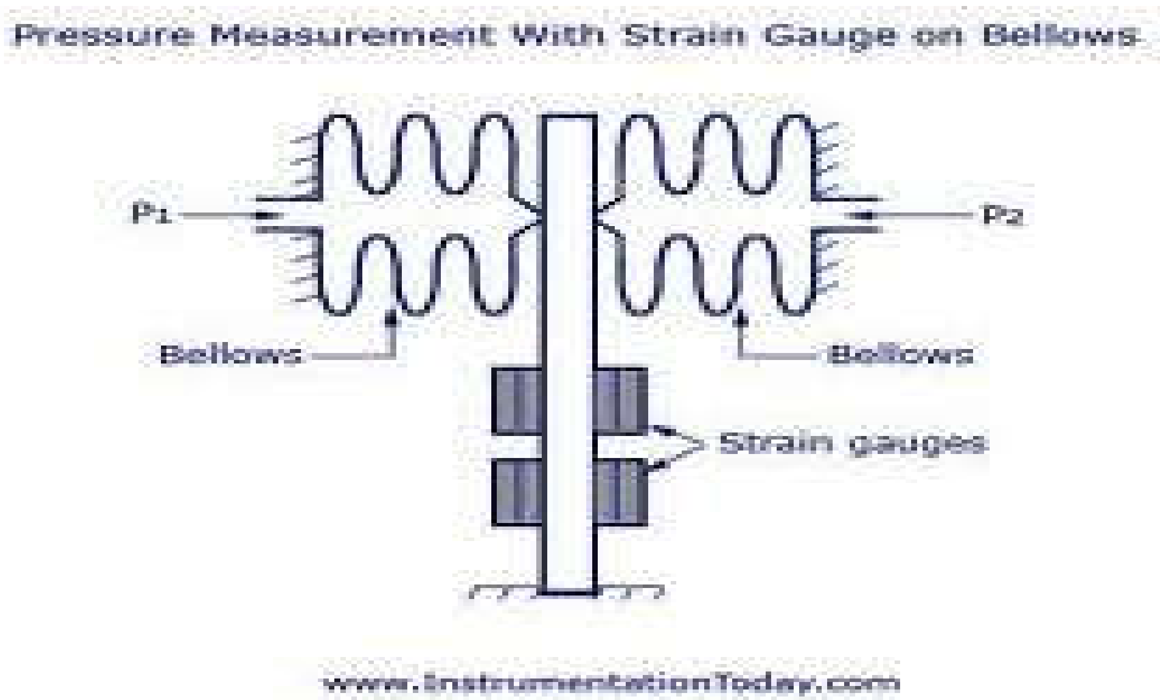
iv. Diaphragm-Strain gauge pressure sensor



More than one strain gage — a tangential sensor and a radial sensor—is mounted to the diaphragm to increase output signal amplitude for a given load.

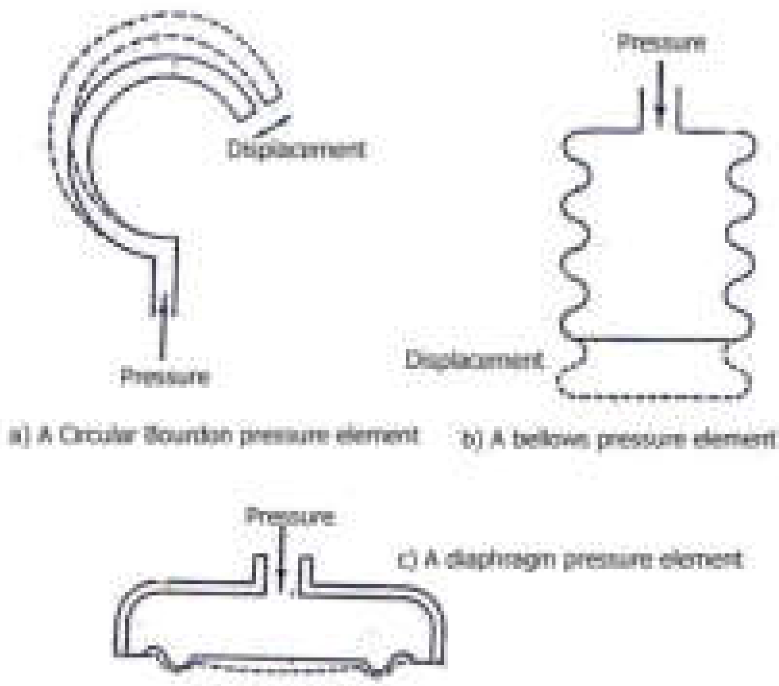
Example 4:

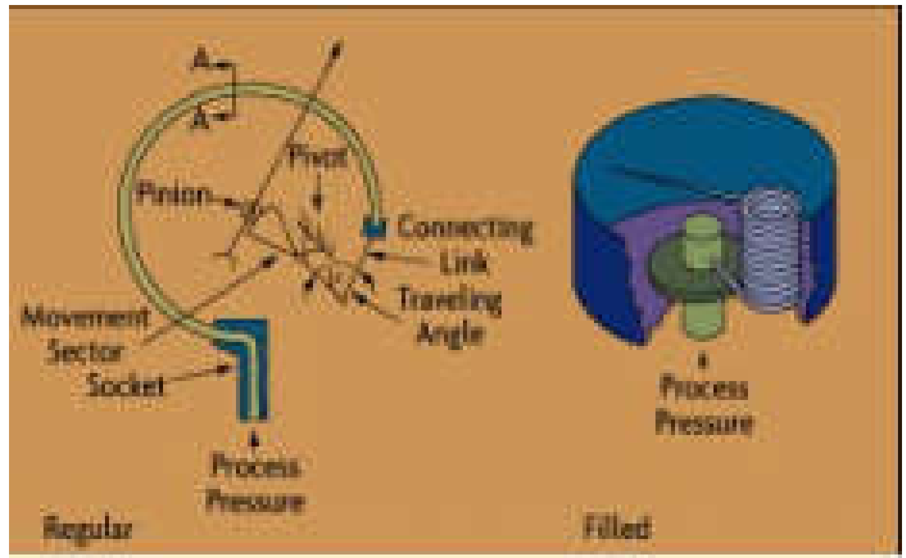
Bellow-Strain gauge differential pressure sensor



Any Question?

Typical Pressure Detector System





The Main Typical Element Used In A Deflection Type Pressure Sensor