

# **MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY**

**(Autonomous Institution – UGC, Govt. of India)**

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‘A’ Grade - ISO 9001:2015 Certified)  
Maisammaguda, Dhulapally (Post Via. Kompally), Secunderabad - 500100,  
Telangana State, India



## **DEPARTMENT OF MECHANICAL ENGINEERING**

**DIGITAL NOTES of MECHANICAL MEASUREMENTS AND CONTROL SYSTEMS**

**For**

**B.Tech – IV YEAR – I sem**

**Prepared by**

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## DIGITAL NOTES

**(R17A0332) MECHANICAL MEASUREMENTS AND CONTROL SYSTEMS****Objectives:**

- To impart knowledge of architecture of the measurement system.
- To deliver working principle of mechanical measurement system.
- To study concept of mathematical modeling of the control system. To analyse control system under different time domain

**UNIT –I**

**Definition** – Basic principles of measurement – Measurement systems, generalized configuration and functional descriptions of measuring instruments – examples. Dynamic performance characteristics – sources of error, Classification and elimination of error.

**Measurement of Displacement:** Theory and construction of various transducers to measure displacement – Piezo electric, Inductive, capacitance, resistance, ionization and Photo electric transducers, Calibration procedures.

**UNIT –II**

**Measurement of Temperature:** Classification – Ranges – Various Principles of measurement – Expansion, Electrical Resistance – Thermistor – Thermocouple – Pyrometers – Temperature Indicators.

**Measurement of Pressure:** Units – classification – different principles used. Manometers, Piston, Bourdon pressure gauges, Bellows – Diaphragm gauges. Low pressure measurement – Thermal conductivity gauges – ionization pressure gauges, Mcleod pressure gauge.

**Measurement of Level:** Direct method – Indirect methods – capacitative, ultrasonic, magnetic, cryogenic fuel level indicators – Bubler level indicators.

**UNIT –III**

**Flow Measurement:** Rotameter, magnetic, Ultrasonic, Turbine flow meter, Hot – wire anemometer, Laser Doppler Anemometer (LDA).

**Measurement of Speed:** Mechanical Tachometers – Electrical tachometers – Stroboscope, Noncontact type of tachometer

**Measurement of Acceleration and Vibration:** Different simple instruments – Principles of Seismic instruments – Vibrometer and accelerometer using this principle.

**UNIT –IV**

**Stress Strain Measurements:** Various types of stress and strain measurements – electrical strain gauge – gauge factor – method of usage of resistance strain gauge for bending compressive and tensile strains – usage for measuring torque, Strain gauge Rosettes.

**Measurement of Humidity** – Moisture content of gases, sling psychrometer, Absorption psychrometer, Dew point meter.

## **UNIT –V**

**Measurement of Force, Torque And Power-** Elastic force meters, load cells, Torsion meters, Dynamometers.

**Elements of Control Systems:** Introduction, Importance – Classification – Open and closed systems Servomechanisms– Examples with block diagrams–Temperature, speed & position control systems.

### **TEXT BOOKS:**

1. Mechanical Measurements / Beck With, Marangoni, Linehar/ PHI Publisher
2. Measurement Systems: Applications & design / D.S Kumar/McGraw Hill Publishers
3. Mechanical Measurements /Shawney/McGraw Hill Publishers

### **REFERENCE BOOKS:**

1. Experimental Methods for Engineers / Holman/ McGraw-Hill Education
2. Mechanical and Industrial Measurements / R.K. Jain/ Khanna Publishers.
3. Instrumentation and Mechanical Measurements / A.K. Tayal / Galgotia Publications.

### **OUTCOMES:**

- Learner should be able to Identify and select proper measuring instrument for specific application Illustrate working principle of measuring instruments.
- Explain calibration methodology and error analysis related to measuring instruments
- Mathematically model and **analyze**.



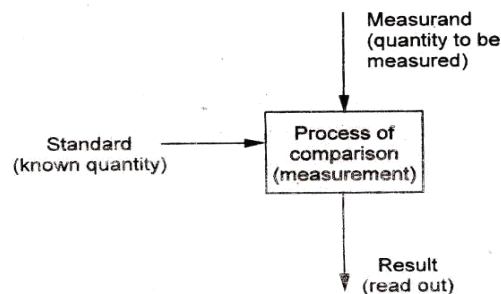
# UNIT- I

## Measurement:-

The old measurement is used to tell us length, weight and temperature are a change of these physical measurement is the result of an opinion formed by one (or) more observes about the relative size (or) intensity of some physical quantities.

### **Definition:**

The word measurement is used to tell us the length, the weight, the temperature, the colour or a change in one of these physical entities of a material. Measurement provides us with means for describing the various physical and chemical parameters of materials in quantitative terms. For example 10 cm length of an object implies that the object is 10 times as large as 1 cm; the unit employed in expressing length.



*Fundamental measuring process*

These are two requirements which are to be satisfied to get good result from the measurement.

1. The standard must be accurately known and internationally accepted.
2. The apparatus and experimental procedure adopted for comparison must be provable.

## Instrumentation:-

### **Definition:**

The human senses cannot provide exact quantitative information about the knowledge of events occurring in our environments. The stringent requirements of precise and accurate measurements in the technological fields have, therefore, led to the development of mechanical aids called instruments.

Or

**Definition:** the technology of using instruments to measure and control physical and chemical properties of materials is called instrumentation.

In the measuring and controlling instruments are combined so that measurements provide impulses for remote automatic action, the result is called control system.

### **Uses:**

- > study the function of different components and determine the cause of all functioning of the system, to formulate certain empirical relations.
- > to test a product on materials for quality control.
- > to discover effective components.
- > to develop new theories.
- > monitor a data in the interest of health and safety.

Ex:- forecasting weather it predicting in the earth case.

**Methods of measurement:-**

1. Direct and indirect measurement.
2. Primary and secondary & tertiary measurement.
3. Contact and non-contact type of measurement.

**1. Direct and indirect measurement:**

Measurement is a process of comparison of the physical quantity with a standard depending upon requirement and based upon the standard employed, these are the two basic methods of measurement.

**Direct measurement:**

The value of the physical parameter is determined by comparing it directly with different standards. The physical standards like mass, length and time are measured by direct measurement.

**Indirect measurement:**

The value of the physical parameter is more generally determined by indirect comparison with the secondary standards through calibration.

The measurement is convert into an analogous signal which subsequently process and fed to the end device at present the result of measurement.

**2. Primary and secondary & tertiary measurement:**

The complexity of an instrument system depending upon measurement being made and upon the accuracy level to which the measurement is needed. Based upon the complexity of the measurement systems, the measurement are generally grouped into three categories.

- i. Primary
- ii. Secondary
- iii. Tertiary.

In the primary mode, the sought value of physical parameter is determined by comparing it directly with reference standards the required information is obtained to sense of side and touch.

Examples are:

- a) Matching of two lengths is determining the length of a object with ruler.
- b) Estimation the temperature difference between the components of the container by inserting fingers.
- c) Use of beam balance measure masses.
- d) Measurement of time by counting a number of strokes of a clock.

Secondary and tertiary measurement are the indirect measurements involving one transmission are called secondary measurements and those involving two convergent are called tertiary measurements.

Ex:

The convergent of pressure into displacement by means of a bellows and the convergent of force into displacement.

Pressure measurement by manometer and the temperature measurement by mercury in glass tube thermometer.

The measurement of static pressure by boundary tube pressure gauge is a typical example of tertiary measurement.

### 3. Contact and non-contact type of measurements:

#### Contact type:

Where the sensing element of measuring device as a contact with medium whose characteristics are being measured.

#### Non-contact type:

Where the sense doesn't communicate physically with the medium.

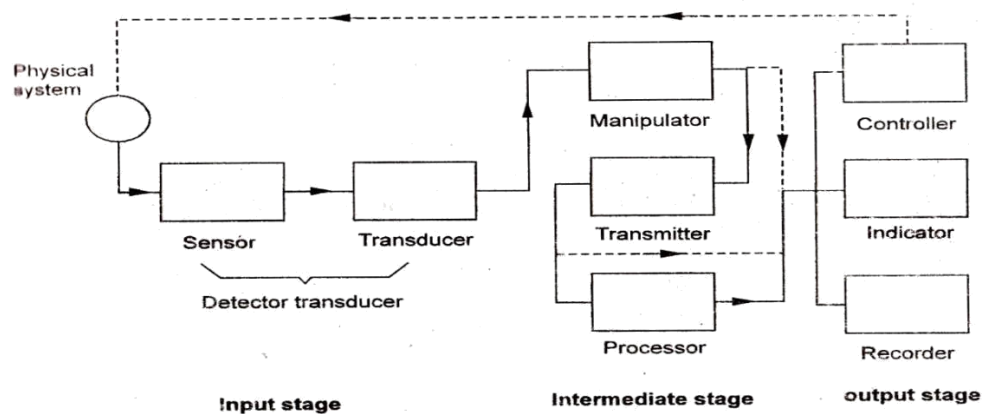
Ex:

The optical, radioactive and some of the electrical/electronic measurement belong to this category.

### Objectives of instrumentation:-

1. The major objective of instrumentation is to measure and control the field parameters to increase safety and efficiency of the process.
2. To achieve good quality.
3. To achieve auto machine and automatic control of process there by reducing human.
4. To maintain the operation of the plan within the design exportations and to achieve good quantity product.

### Generalised measurement system and its functional elements:-



*Generalised measurement system*

- 1) Primary sensing element.
- 2) Variable conversion (or) Transducer element.
- 3) Manipulation of element.
- 4) Data transmission element.
- 5) Data processing element.

## 6) Data presentation element.

The principal functions of an instrument is the acquisition of information by Sensing and perception, the process of that information and its final presentation to a Human observer. For the purpose of analysis and synthesis, the instrument s are considered as systems (or) assembly of inter connected components organised to perform a specified function. The different components are called elements.

### 1) PIMARY SENSING ELEMENT:

An element that is sensitive to the measured variable .The sensing element sense the condition , state (or) value of the process variable by extracting a small part of energy from the measurement and produces an output which is proportional to the input. Because of the energy expansion, the measured quantity is always disturb. Good instruments are designed to minimise this loading effect.

### 2) Variable conversion (or) transducer element:

An element that converts the signal from one physical for to Another without changing the information content of the signal.

Example:

- Bourdon tube and bellows which transfer pressure into displacement.
- Proving ring and other elastic members which converts force into displacement.
- Rack and Pinion: It converts rotary to linear and vice versa.
- Thermo couple which converts information about temperature difference to information in the form of E.M.F.

### 3) MANIPULATION ELEMENT:

It modifies the direct signal by amplification, filtering etc., so that a desired output is produced.

$$[\text{input}] \times \text{constant} = \text{Output}$$

### 4) DATA TRANSMISSION ELEMENT:

An element that transmits the signal from one location to another without changing the information content. Data may by transmitted over long distances (from one location to another) or short distances (from a test centre to a nearby computer).

### 5) DATA PROCESSING ELEMENT:

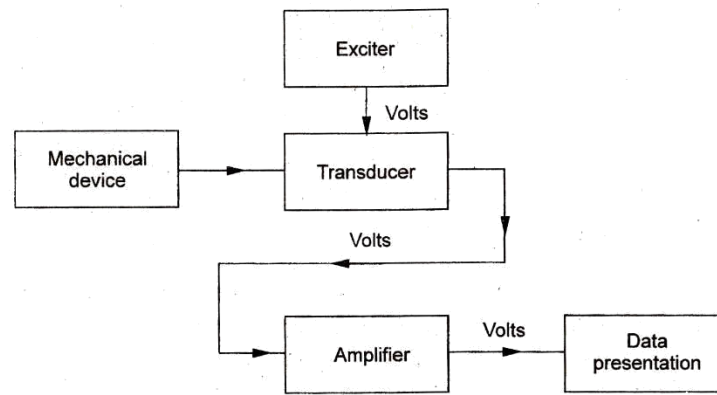
An element that modifies data before it is displayed or finally recorded. Data processing may be used for such purposes as:



Corrections to the measured physical variables to compensate for scaling, non-linearity, zero offset, temperature error etc.

- ✓ Convert the data into useful form, e.g., calculation of engine efficiency from speed, power input and torque developed.
- ✓ Collect information regarding average, statistical and logarithmic values.

## 6) DATA PRESENTATION ELEMENT:



*Electro-mechanical measurement system*

An element that provides record or indication of the output from the data processing element. In a measuring system using electrical instrumentation, an exciter and an amplifier are also incorporated into the circuit.

The display unit may be required to serve the following functions.

- ✓ transmitting
- ✓ Signalling
- ✓ Registering
- ✓ Indicating
- ✓ recording

The generalised measurement system is classified into 3 stages:

a) Input Stage

b) Intermediate Stage

- i. Signal Amplifications
- ii. Signal Filtration
- iii. Signal Modification
- iv. Data Transmission

c) Output Stage

### a) Input Stage:

Input stage (Detector-transducer) which is acted upon by the input signal (a variable to be measured) such as length, pressure, temperature, angle etc. and which transforms this signal in some other physical form. When the dimensional units for the input and output signals are same, this functional element/stage is referred to as the transformer.

### b) Intermediate Stage:

i. signal amplification to increase the power or amplitude of the signal without affecting its waveform. The output from the detector-transducer element' is generally too small to operate an indicator or a recorder and its amplification is necessary. Depending upon the type of transducer signal, the amplification device may be of mechanical, hydraulic/pneumatic, optical and electrical type.

ii. Signal filtration to extract the desired information from extraneous data. Signal filtration removes the unwanted noise signals that tend to obscure the transducer signal. Depending upon nature of the signal and situation, one may use mechanical, pneumatic or electrical filters.

iii. Signal modification to provide a digital signal from an analog signal or vice versa, or change the form of output from voltage to frequency or from voltage to current.

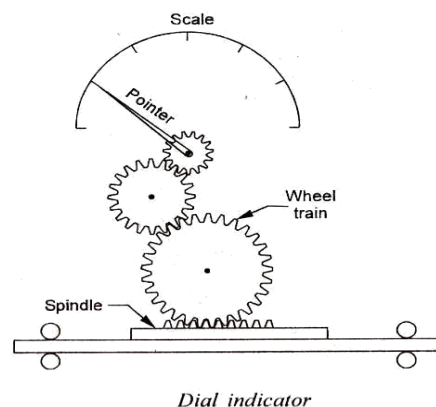
iv. Data transmission to telemeter the data for remote reading and recording.

### c) Output Stage:

which constitutes the data display record or control. The data presentation stage collects the output from the signal-conditioning element and presents the same to be read or seen and noted by the experimenter for analysis. This element may be of:-

- ✓ visual display type such as the height of liquid in a manometer or the position of pointer on a scale
- ✓ numerical readout on an electrical instrument
- ✓ Graphic record on some kind of paper chart or a magnetic tape.

Example: Dial indicator



## **CLASSIFICATION OF INSTRUMENTS:-**

- 1) Automatic and Manual instruments:
- 2) Self generating and power operated
- 3) Self contact and remote indicating instruments
- 4) Deflection and null type
- 5) Analog and digital types
- 6) Contact and no-contact type

### **1) Automatic and manual instruments:**

The manual instruments require the services of an operator while the automatic types donot. For example, the temperature measurement by mercury-in-glass thermometer is automatic as the instrument indicates the temperature without requiring any manual assistance. However, the measurement of temperature by a resistance thermometer incorporating; Wheatstone brigde in its circuit is manual in operation as it needs an operator for obtaining the null position.

### **2) Self generating and power operated**

Self-generated instruments are the output is supplied entirely by the input signal. The instrument does not require any out side power in performing its function

Example: mercury in glass thermometer, bourdon pressure gauge, pitot tube for measuring velocity

So instruments require same auxillary source of power such as compound air, electricity, hydraulic supply for these operations and hence are called externally powered instruments (or) passive instruments.

Example:

- L.V.D.T(Linear Variable Differential Transducer)
- Strain gauge load cell
- Resistance thermometer and the mister.
- Self contained remote indicator.

### **3) Self contact and remote indicating instruments:**

The different elements of a self-contained instrument are contained in one physical assembly. In a remote indicating instrument, the primary sensing element may be located at a sufficiently long distance from the secondary indicating element. In the modern instrumentation technology, there is a trend to instalremote indicating instruments where the important indications can be displayed in the central control rooms.

#### 4) Deflection and null output instruments:

In null-type instruments, the physical effect caused by the quantity being measured is nullified (deflection maintained at zero) by generating an equivalent opposing effect. The equivalent null causing effect then provides a measure of the unknown quantity. A deflection type instrument is that in which the physical effect generated by the measuring quantity (measurand) is noted and correlated to the measurand.

#### 5) Analog and digital instruments:

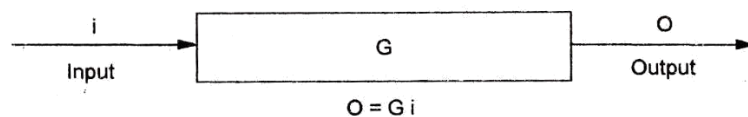
The signals of an analog unit vary in a continuous fashion and can take on infinite number of values in a given range. Wrist watch speedometer of an automobile, fuel gauge, ammeters and voltmeters are examples of analog instruments.

Instruments basically perform two functions:

- (i) Collection of data and
- (ii) control of plant and process

Accordingly based upon the service rendered, the instruments may also be classified as indicating instruments, recording instruments and controlling instruments.

#### INPUT, OUTPUT CONFIGURATION OF A MEASURING INSTRUMENT:-



*Input-output relation of a measurement system*

An instrument performs an operation on an input quantity (measurement/designed variable) to provide an output called the measurements. The input is denoted by “i” and the output is denoted by “o”. According to the performance of the instrument can be stated in terms of an operational transfer function(G).The input and output relationship is characterised by the operation ‘G’ such that

$$o = G i$$

The various inputs to a measurement system can be classified into-three categories:

##### **i) Desired input:**

A quantity that the instrument is specifically intended to measure. The desired input produces an output component according to an input-output relation symbolised by ; here represents the mathematical operation necessary to obtain the output from the input.



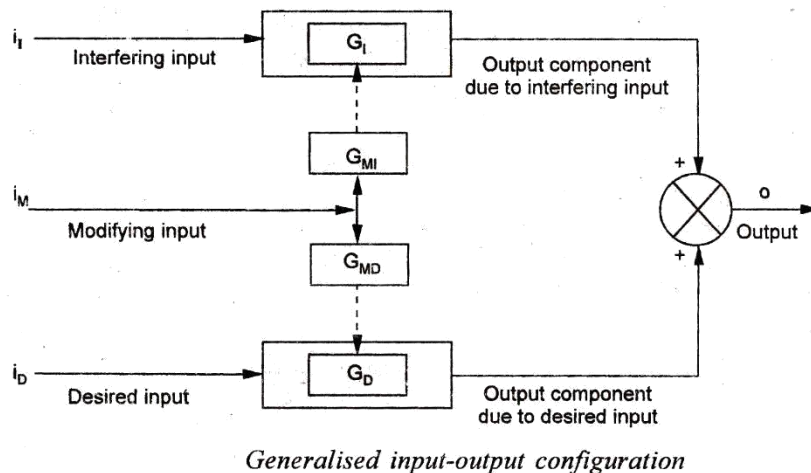
## ii) Interfering input:

A quantity to which the instrument is unintentionally sensitive. The interfering input would produce an output component according to input-output relation symbolised by

## iii) Modifying input:

A quantity that modifies the input-output relationship for both the desired and interfering inputs. The modifying input would cause a change in and/or . The specific manner in which affects and  $G$ , is represented by the symbols and , respectively.

A block diagram of these various aspects has been illustrated in Fig.



## Example:

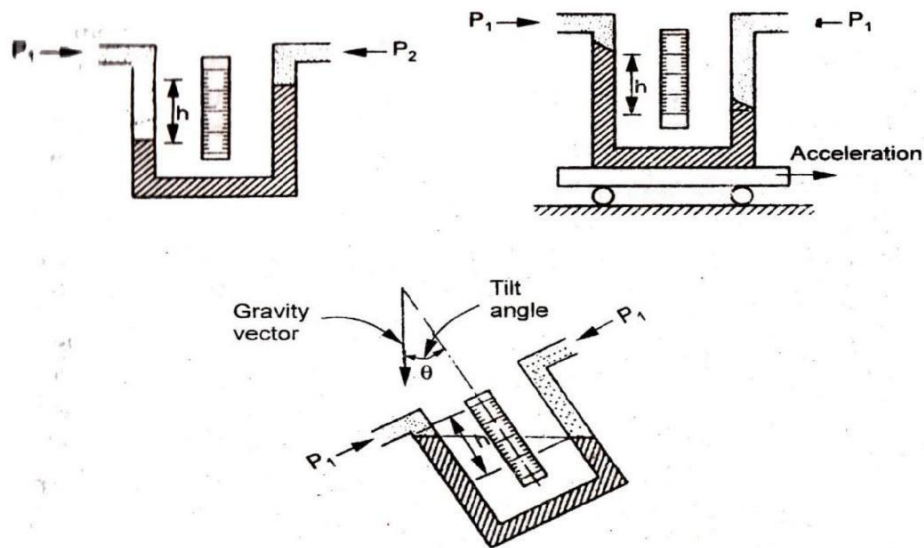
Consider a differential manometer which consists of an u-tube filled with mercury and with its ends connected to the two points between which the pressure differential is to be measured. The pressure differential  $p_1 - p_2$  is worked out from the hydro static (Equilibrium) equation:

$$(p_1 - p_2) = g h (\rho_m - \rho_f)$$

and are the mass densities of mercury and fluid respectively, and  $h$  is the scale reading. If the fluid flowing in the pipeline is a gas, then << accordingly the above identity can be re-written as

$$(p_1 - p_2) = g h \rho_m$$

Here differential pressure is  $p_1 - p_2$  is the desired input; Scale reading 'h' is the output and is the parameter which relates the output and the input.



*Spurious inputs for a manometer*

A) The manometer is placed on a wheel which is subjected to acceleration and scale indicates a reading even though the pressures  $P_1$  &  $P_2$  at the two ends are equal.

The acceleration that constitutes the interference input. The manometer has an angular tilt i.e., is not properly align with the direction of the gravitational force.

An output will result even when there is no pressure difference. Here the angular tilt acts as the interfering input.

Here scale factor establishes the input - output relation and this gets modified due to

- i) Temperature variation which change the value of density of mercury.
- ii) Change in gravitational force due to change in location of a manometer. So, these 2 are modifying quantities.

- 1) Signal filtering
- 2) Compensation by opposing inputs.
- 3) Output correction.

#### **Performance characteristics of a measuring instrument:-**

- 1. Static characteristics
- 2. Dynamic characteristics

The performance characteristics of an instrument system is conclusion by low accurately the system measures the requires input and how absolutely it reject the undesirable inputs.

Error = measured value ( ) – true value ( )

Correction = ( - ).

### **1. Static characteristics:**

a) Range and span, b) Accuracy, error, correction, c) Calibration, d) Repeatability, e) Reproducibility

f) Precision, g) Sensitivity, h) Threshold, i) Resolution, j) Drift, k) Hysteresis, dead zone.

#### **a) Range and span**

The region between the limits with in which as instrument is designed to operate for measuring, indicating (or) recording a physical quantity is called the range of instrument. The range is expressed by standing the lower and upper values. Span represents the algebraic difference between the upper and lower range values of the instruments.

**Ex: -**

Range - 10 C<sup>o</sup> to 80 C<sup>o</sup>      Span=90<sup>o</sup>c

Range 5 bar to 100 bar      Span=100-5=95 bar

Range 0 v to 75v      Span=75volts

#### **b) Accuracy, error, correction:**

No instrument gives an exact value of what is being measured, there is always some uncertainty in the measured values. This uncertainty express in terms of accuracy and error.

Accuracy of an indicated value (measured) may be defined as closeness to an accepted standard value (true value). The difference between measured value ( ) and true value ( ) of the quantity is expressed as instrument error.

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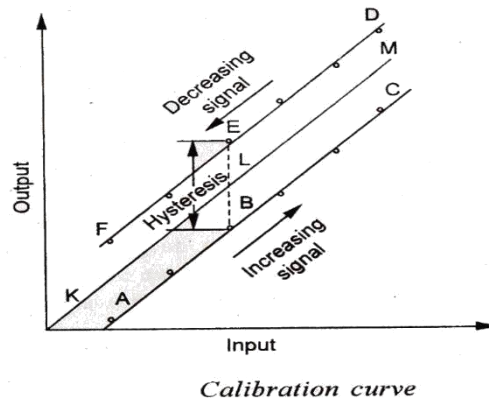
Static correction is defined as -

= -

#### **c) Calibration:**

The magnitude of the error and consequently the correction to be applied is determined by making a periodic comparison of the instrument with standards which are known to be constant. The entire procedure laid down for making, adjusting or checking a scale so that readings of an instrument or

measurement system conform to an Accepted standard is called the calibration. The graphical representation of the calibration record is called calibration curve and this curve relates standard values of input or measurand to actual values of output throughout the operating range of the instrument. A comparison of the instrument reading may be made with



- (i) a primary standard,
- (ii) a secondary standard of accuracy greater than the instrument to be calibrated,
- (iii) a known input source.

The following points and observations need consideration while calibrating an instrument:-

- (a) Calibration of the instrument is out with the instrument in the same (upright, horizontal etc.) and subjected same temperature and other environmental conditions under which it is to operate while in service.
- (b) The instrument is calibrated with values of the measuring impressed both in the increasing and in the decreasing order. The results are then expressed graphically, typically the output is plotted as the ordinate and the input or measuring as the abscissa.
- (c) Output readings for a series of impressed values going up the scale may not agree with the output readings for the same input values when going down.
- (d) Lines or curves plotted in the graphs may not close to form a loop.

#### **d) Repeatability:**

Repeatability describes the closeness of the output readings, when the same input is applied repeatability over a short period of time with the same measurement conditions, same instrument and observer, same location and same conditions of use maintained throughout.

**e) Reproducibility:** Reproducibility describes the closeness of output readings for the same input. When are changes in the method of measurement, observer, measuring instrument, location, conditions of use and time of measurement.

**f) Precision:**

The instrument ability to reproduce a certain group of the readings with a given accuracy is known as precision i.e., if a no of measurements are made on the same true value then the degree of closeness of these measurements is called precision.

It refers to the ability of an instrument to give its readings again and again in the same manner for constant input signals.

**g) Sensitivity:**

Sensitivity of an instrument is the ratio of magnitude of response (output signal) to the magnitude of the quantity being measured (input signal) i.e.,

$$\text{Static sensitivity} = \frac{\text{change of output signal}}{\text{change of input signal}} = \frac{\Delta O}{\Delta I}$$

**h) Threshold:**

Threshold defines the minimum value of input which is necessary to cause detectable change from zero output.

When the input to an instrument is gradually increased from zero, then the input must reach to a certain minimum value, so that the change in the output can be detected. The minimum value of input refers to threshold.

**i) Resolution:**

It is defines as the increment in the input of the instrument for which input remains constant i.e., when the input given to the instrument is slowly increased for which the output remains same until the increment exceeds a different value.

**j) Drift:**

The slow variation of the output signal of a measuring instrument is known as draft.

The variation of the output signal is not due to any changes in the input quantity, but to the changes in the working conditions of the components inside the measuring instruments.

**k) Hysteresis, Dead zone:**

Hysteresis is the maximum difference for the same measuring quantity (input signal) between the up scale and down scale reading during a full range measure in each direction.

Dead zone is the largest range through which an input signal can be varied without initiating any response from the indicating instrument it is due to the friction.

## **2. Dynamic characteristics:**

a) Speed of response and measuring lag, b) Fidelity and dynamic error, c) Over shoot, d) Dead time and dead zone, e) Frequency response.

### **a) Speed of response and measuring lag:**

In a measuring instrument the speed of response (or) responsiveness is defined as the rapidity with which an instrument responds to a change in the value of the quantity being measured.

Measuring lag refers to delay in the responds of an instrument to a change in the input signal. The lag is caused by conditions such as inertia, or resistance.

### **b) Fidelity and dynamic errors:**

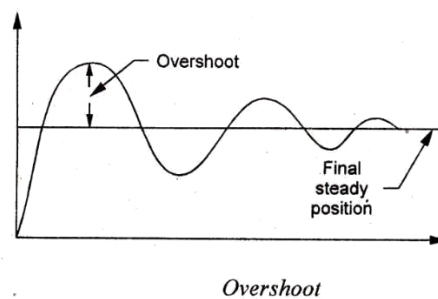
Fidelity of an instrumentation system is defined as the degree of closeness with which the system indicates (or) records the signal which is upon its. It refers to the ability of the system to reproduce the output in the same form as the input. If the input is a sine wave then for 100% fidelity the output should also be a sine wave.

The difference between the indicated quantity and the true value of the time quantity is the dynamic error. Here the static error of instrument is assumed to be zero.

### **c) Over shoot:**

Because of maximum and inertia. A moving part i.e., the pointer of the instrument does not immediately came to rest in the find deflected position. The pointer goes find deflected position. The pointer goes beyond the steady state i.e., it over shoots.

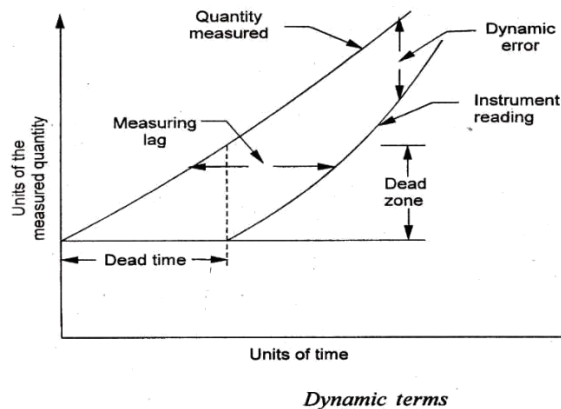
The over shoot is defined as the maximum amount by which the pointer moves beyond the steady state.



### **d) dead time and dead zone:**

Dead time is defined as the time required for an instrument to begin to respond to a change in the measured quantity it represent the time before the instrument begins to respond after the measured quantity has been altered.

Dead zone define the largest change of the measured to which the instrument does not respond. Dead zone is the result as friction backlash in the instrument.



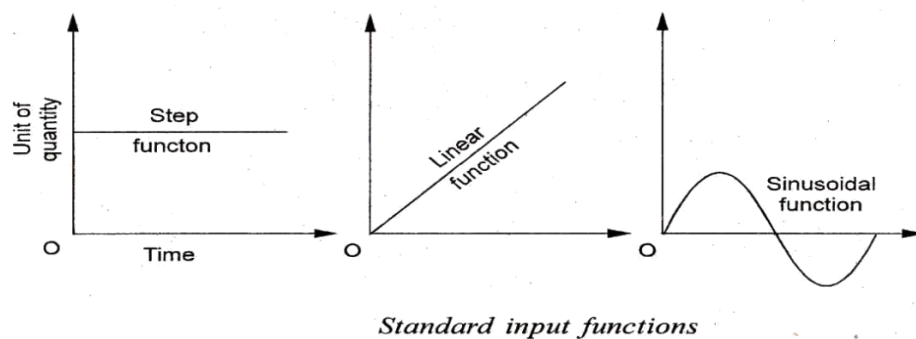
#### e) Frequency response:

(The dynamic performance of both measuring and control system is determine by applying some known and predetermined input signal to its primary sensing element and them)

Maximum frequency of the measured variable that an instrument is capable of following with error. The usual requirement is that the frequencies of the measured should not exceed 60% of the natural frequency measuring instrument.

#### Standard test inputs:

The dynamic performance of both measuring and control system is determined by applying some known and predetermined input signal to its primary sensing element and then studying the behaviour of the output signals.



The most common standard inputs used for dynamic analysis

- i. Step functions
- ii. Linear (or) ramp functions
- iii. Sinusoidal (or) sine wave functions

### i. Step function:

Which is a sudden change from one steady value to another the step input is mathematically represented by

Where  $\theta_i = 0$  at  $t < 0$

ii. Ramp (or) linear function:  $\theta_i = \theta_0$  at  $t \geq 0$

The input varies linearly with time. The ramp input is mathematically represented as

Where  $\Omega$  slope of the input versus time relationship.

### iii. Sinusoidal (or) sine wave function:

Here the input has a cycle variation, the input varies sinusoidal with a constant amplitude mathematically it may be represented as

$$\theta_i = A \sin \omega t$$

where  $A$  is the amplitude and  $\omega$  is the frequency in rad/s.

The frequency or harmonic response is a measure of the capability of the system to respond to inputs of cyclic nature.

A general measurement system can be mathematically described by the following differential equation

$$(A_n D^n + A_{n-1} D^{n-1} + \dots A_1 D + A_0) \theta_o$$

$$(B_m D^m + B_{m-1} D^{m-1} + \dots B_1 D + B_0) \theta_i$$

where the  $A$ 's and  $B$ 's are constants depending upon the physical parameter of the system

$D^k$  is the operative derivative of the order  $k$ ,

$\theta_o$  is the information out of the measurement system, and

$\theta_i$  is the input information

The time factor in the input or driving function may correspond to step input, ramp input, sinusoidal input or any combination of these.

The order of the measurement system is generally classified by the value of the power of  $n$

- \* Zero order system :  $n = 0$  and  $A_1, A_2, \dots, A_n = 0$
- \* First order system :  $n = 1$  and  $A_2, A_3, \dots, A_n = 0$
- \* Second order system :  $n = 2$  and  $A_3, A_4, \dots, A_n = 0$



### Zero, first and second order systems:-

**Zero order system :** Consider an ideal measuring system, *i.e.*, a system whose output is directly proportional to input ; no matter how the input varies. The output is a faithful reproduction of input without any distortion or time lag. The mathematical equation relating output to input is of the form

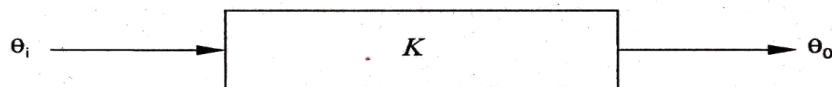
$$\theta_o = K \theta_i$$

where  $K$  is the sensitivity of the system. This equation of the zero order system is obtained when the power of  $n$  is set equal to zero in the general equation for a measurement system.

That gives :  $A_0 \theta_o = B_0 \theta_i$

$$\text{or } \theta_o = \frac{B_0}{A_0} \theta_i = K \theta_i$$

The static sensitivity is the only parameter which characterises a zero order system and its value can be obtained through the process of static calibration. A block diagram representing zero-order systems has been shown in Fig. 2.12(a)



*Block diagram for a zero system*

Some examples of zero-order system are :

- \* mechanical levers,
- \* amplifiers, and
- \* potentiometer which gives an output voltage proportional to the displacement of the wiper.

### **First Order Systems:**

The behaviour of a first order system is represented by a first order differential equation of the form.

$$A_1 \frac{d\theta_o}{dt} + A_0 \theta_o = B_0 \theta_i$$

(obtained by substituting  $n=1$  in general equation)

This may be manipulated to rewrite in the following standard form :

$$\frac{A_1}{A_0} \frac{d\theta_o}{dt} + \theta_o = \frac{B_0}{A_0} \theta_i$$

$$\tau \frac{d\theta_o}{dt} + \theta_o = K \theta_i$$

where  $\tau$  is the time constant ( $\tau = A_1/A_0$ ) and  $K$  is the static sensitivity ( $K = B_0/A_0$ )

In terms of  $D$ -operator where

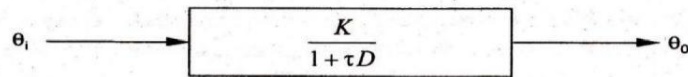
$$D = \frac{d}{dt} \text{ and } D^2 = \frac{d^2}{dt^2}$$

we have :

$$\tau D \theta_o + \theta_o = K \theta_i \quad ; \quad (\tau D + 1) \theta_o = K \theta_i$$

$$\frac{\theta_o}{\theta_i} = \frac{K}{(\tau D + 1)} \quad \text{----- } 2.10$$

Equation 2.20 represents the standard form of transfer operator for the first-order system ; its block diagram has been indicated in Fig 2.12(b).



*Block diagram for a first order system*

Some examples of the first-order system are :

- temperature measurement by mercury-in-glass thermometers, thermocouples and thermistors
- build-up of air pressure in bellows
- network of resistance-capacitance
- velocity of a free falling mass

**Second-order systems :** The input/output relationship of a second order system is described by a differential equation of the form

$$A_2 \frac{d^2\theta_0}{dt^2} + A_1 \frac{d\theta_0}{dt} + A_0\theta_0 = B_0\theta_i$$

(obtained by substituting  $n=2$  in the general equation)

Dividing both sides by  $A_0$  and letting

$$\omega_n = \sqrt{\frac{A_0}{A_2}} = \text{undamped natural frequency, rad/s}$$

$$\zeta = \frac{A_1}{2\sqrt{A_0A_2}} = \text{damping ratio, dimensionless}$$

$$K = \frac{B_0}{A_0} = \text{static sensitivity or steady state gain}$$

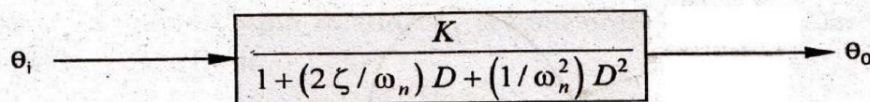
we obtain :

$$\frac{1}{\omega_n^2} \frac{d^2\theta_0}{dt^2} + \frac{2\zeta}{\omega_n} \frac{d\theta_0}{dt} + \theta_0 = K\theta_i$$

In terms of  $D$ -operator

$$\left( \frac{D^2}{\omega_n^2} + \frac{2\zeta}{\omega_n} D + 1 \right) \theta_0 = K\theta_i$$

or  $\frac{\theta_0}{\theta_i} = \frac{K}{\frac{1}{\omega_n^2} D^2 + \frac{2\zeta}{\omega_n} D + 1}$  2.23



*Block diagram for a second order system*

Equation 2.23 represents the standard form of transfer operator of the second-order system; its block diagram has been indicated in Fig. 2.12(c).

Some examples of second-order instruments are :

- \* spring-mass system employed for acceleration and force measurements,
- \* piezo electric pick ups,
- \* U.V. galvanometer, and
- \* pen control system on X-Y plotters

Most of the mechanical instruments invariably consist of a spring and a moving mass, and their combination provides a system which will oscillate naturally at a given frequency. The amplitude of the oscillation is affected by damping which is a means of dissipating energy in the system.

#### Sources of error:

1. Calibration of Instrument
2. Instrument reproducibility
3. Measuring arrangement
4. Work piece
5. Environmental condition
6. Observes skill

#### **1. Calibration of Instrument:**

For any instrument calibration is necessary before starting the process of measurement. When the instrument is load frequently for long time, the calibration of instrument is used frequently for long time, the calibration of instrument may get disturbed. The instrument which is gone out of b ration cannot give actual value of the measured. Therefore the output produced by such an instrument have error. The error due to improper calibration of instrument is known as systematic instrumental error, and it occurs regularly.

Therefore this error can be eliminated by, properly calibrating the instrument at frequent intervals.

#### **2. Instrument reproducibility:**

Though an instrument is calibrated perfectly under group of conditions, the output produced by that instrument contains error. This occurs if the instrument is used under those set of conditions which are not identical to the conditions existing during calibration. i.e., the instrument should be used under those set of conditions at which -.the instrument is calibrated. This type of error may occur systematically or accidentally.

#### **3. Measuring arrangement:**

The process of measurement itself acts as a source of error if the arrangement of different components of a measuring instrument is not proper.

Example:

While measuring length, the comparator law of Abbe should be followed. According to this, actual value of length is obtained when measuring instrument and scale axes are collinear, and any misalignment of these will give error value. Hence this type of error can be eliminated by having proper arrangement of measuring instrument.

#### **4. Work piece:**

The physical nature of object (work piece) i.e., roughness, softness and hardness of the object acts as a source of error. Many optomechanical and mechanical type of instruments contact the. Object under certain fixed pressure conditions. Since the response of soft and hard objects under these fixed conditions is different the output of measurement will be in error.

#### **5. Environmental condition:**

Changes in the environmental conditions is also a major source of error. The environmental conditions such as temperature, humidity, pressure, magnetic or electrostatic field surrounding the instrument may affect the instrumental characteristics. Due to this the result produced by the measurement may contain error.

There errors are undesirable and can be reduced by the following ways,

- (a) Arrangement must be made to keep the conditions approximately constant.
- (b) Employing hermetically sealing to certain components in the instrument, which eliminate the effects of the humidity, dust, etc.
- (c) Magnetic and electrostatic shields must be provided.

#### **6. Observes skill:**

It is a well-known fact that the output of measurement of a physical quantity is different from operator to operator and sometimes even for the same operator the result may vary with sentimental and physical states. One of the examples of error produced by the operator is parallax error in reading a meter scale. To minimize parallax errors modern electrical instruments have digital display of output.

#### **Classification of errors and elimination of errors:**

No measurement can be made with perfect accuracy but it is important to find out what accuracy is and how different errors have entered into the measurement. A study of errors is a first step in finding ways to reduce them. Errors may arise from different sources and are usually classified as under.

1. Gross errors
2. Systematic (or) instrumental errors
3. Random (or) environmental errors

### **1. gross errors:**

This cause of errors mainly covers human mistakes in reading instruments and recording and calculating measurement result. The responsibility of the mistake normally lies with the experimental.

Ex: The temperature is  $31.5^{\circ}\text{C}$ , but it will write as  $21.5^{\circ}\text{C}$  its an error how ever they can be avoided by adopting two means

1. Great care should be taken in reading and recording the data.
2. Two, three (or) even more readings should be taken for quantity under measurement

### **2. systematic errors:**

These type of errors are divided into three categories.

- a. Instrumental errors
- b. Environmental errors
- c. Observational errors

#### **a. Instrumentation errors:**

These errors occurs due to three main reasons.

- a. Due to inherent short comings of the instrument
- b. Due to misuse of instruments
- c. Due to loading effects of instruments.

#### **b. Environmental errors:**

These errors are caused due to changes in the environmental conditions in the area surrounding the instrument, that may affect the instrument characteristics, such as the affects of changes in temperature, humidity, barometric pressure or if magnetic field or electrostatic field.

These undesirable errors can be reduced by the following ways.

- (i) Arrangement must be made to keep the conditions approximately constant.
- (ii) Employing hermetically sealing to certain components in the instrument, which eliminate the effects of the humidity dust, etc.
- (iii) Magnetic or electrostatic shields must be provided.

#### **c. Observational errors:**

These errors are produced by the experiment. Enter. The most frequent error is the parallax error introduced in reading a meter scale.

These errors are caused by the habits of individual observers To minimize parallax errors modern electrical instruments have digital display of output.

### **3. Random (or) accidental errors:**

The causes of such errors is unknown (or) not determinable in the ordinary process making measurements. Such errors are normally small and follow the law of chance. Random errors they may be treated mathematically according to the law of probability.

- a. Certain human errors
- b. Errors caused due to the disturbances to the equipment's
- c. Errors caused by fluctuating experimental conditions.

#### **a. Certain human errors:**

These errors occur due to inconsistency in estimating successive readings from the instrument by an experimenter. To reduce these errors it is necessary to exercise extreme care with mature and considered judgement in recording the observations.

#### **b. Errors caused due to the disturbances to the equipment:**

Precision errors in the instrument may arise from the outside disturbances to the measuring system. These disturbances may be variations or mechanical vibrations. Poorly controlled processes also lead to random errors.

#### **c. Errors caused by fluctuating experimental conditions:**

These errors are caused due to some uncontrolled, disturbances which influence the instrument output. Line voltage fluctuations, vibrations of the instrument supports, etc., are common examples of this type.

## **Measurement of displacement:-**

### **Introduction:**

The direct measurements of displacement, force, torque and speed are very important in industrial processes. Also. Many other quantities such as pressure, temperature, level, flow, etc. are often measured by transducers them to displacement. Motion, or force, and then measuring these parameters which give the required value of a particular quantity. In this chapter some of the methods for measuring displacement, force, torque and speed have been discussed.

### **Measurement of displacement:**

Generally, displacement is thought of in terms of motion of a few millimeters (mm) or less. The measurement of displacement is made frequently to relate to some other measurement and hence displacement transducers are fundamental components of any instrumentation system Displacement is closely associated with motion (from one point to another) and position (i.e. a change from one position to the next). Displacement can be measured by both mechanical and electrical methods, but only electrical methods which are common in industrial use will be described here.

**Definition of a Transducer:**

Strain gauge is a positive-type resistance transducer which converts a mechanical displacement into a change of resistance. It is the most commonly used transducer for the measurement of displacement. The resistance gauge is essentially a fine wire which changes its resistance, when mechanically strained.

Due to physical effects. Its length and cross-sectional area vary and a change of electrical resistivity also occurs.

A transducer perform the following functions:

- i. detects or senses the present and changes in physical quantity being measured.
- ii. Provided a proportional output signal.

The strain Range is mounted to the measured surface so that it elongates or contracts with that surface. This deformation of the sensing materials causes it to undergo a change in resistance.

### **Classification of transducers:-**

✚ Transducers are broadly classified into two groups as follows:

3. Active transducers (self-generating type)
4. Passive transducers (Externally powered)

#### **1. Active transducers (self-generating type):**

Active transducers are self-generating type. They do not required electric energy. They work on the principle of conservation of energy. The energy required for production of an output signal is obtained from the input or physical phenomenon being measured.

Examples: Thermo couples, Thermoelectric and Piezo-electric devices....etc.

#### **2. Passive transducers (Externally powered):**

Passive transducers are externally powered type. Passive transducers are based on principle of energy controlling and they required a secondary electrical source for operation.

Examples: LVDT (Linear variable differential transformer), Thermistors, resistance thermometers, strain gauge devices.

✚ **Classification based on the type of output:**

- b) Analog Transducer
- c) Digital Transducer

#### **1. Analog Transducer:**

These transducers convert the input physical phenomenon into an analog output (analog form) which is continuous function of time.

Examples: Thermistor, Thermocouple, strain gauge, LVDT.



## 2. Digital Transducer:

These transducers convert the input physical phenomenon into an electrical output (digital form) which may be in the form of pulses.

Examples: Turbine flow meter.



### Classification based on the electrical principle involved:

#### g) Variable resistance type

Strain and pressure gauge

Thermistors, resistance thermo meters

Photo conductive cell

#### h) Variable inductance type

LVDT

Reluctance pickup

Eddy current type

#### i) Variable capacitance type

Capacitor micro phase

Pressure gauge

Di electric gauge

#### j) Voltage generating type

Thermo couple

Photo voltaic cell

Rotational motion tachometer

Piezo- electric pickup

#### k) Voltage divider type

Potentiometer position sensor

Pressure actuated voltage divider



### According to the principle of operation, transducer for the measurement of displacement:

- (iv) Variable resistance transducer
- (v) Variable inductance transducer
- (vi) Variable capacitance transducer
- (vii) Piezo electric transducer
- (viii) Photo electric or light detecting transducer

Photo conductive

Photo voltaic

Photo emissive

- (ix) Ionization transducers.

#### **Advantages of electrical transducers over other transducers:**

- (c) Mass and inertia effects are minimized
- (d) Amplification or attenuation is minimized
- (e) Effect of friction is minimized
- (f) They are compact in size
- (g) Remote indication is possible
- (h) Power consumption is less and loading errors are minimized.

#### **Limitations:-**

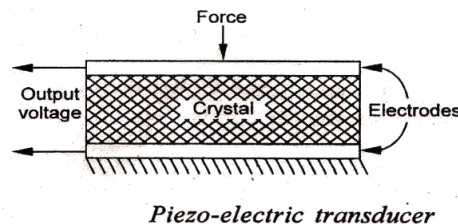
1. They need external power supply, 2. High cost

f) Instrument electrical properties may change the actual reading of the variable which is to be measured.

#### **Piezo Electric transducers:-**

##### **Piezo electric transducers**

Piezo-electricity represents the property of a number of crystalline materials that cause the crystal to develop an electric charge or potential difference when subjected to mechanical forces or stresses along specific planes. Conversely, the crystal would undergo change in



thickness (and thus produce mechanical forces) when charged electrically by a potential difference applied to its proper axis. Elements exhibiting piezo-electric qualities are sometimes known as electro restrictive elements.

A typical mode of operation of a piezo electric device for measuring varying force applied to a simple plate is shown in Fig. Metal electrodes are attached to the selected faces of a crystal in order to detect the electrical charge developed. The magnitude and Polarity of the induced charge on the crystal surface is proportional to the magnitude and direction of the applied force and is given by :

$$Q = K F$$

Where Q is the charge in coulomb, F is the impressed force in newtons and K is the crystal sensitivity in C/N; it is constant for particular crystals and the manner in which they are cut. The relationship between the force F and the change  $\delta t$  in the crystal thickness t is given by the stress-strain relationship.

$$\text{Young's modulus} = \frac{\text{stress}}{\text{strain}} ; \quad Y = \frac{F/A}{\delta t/t}$$

$$F = A Y \frac{\delta t}{t}$$

The charge at electrode gives rise to voltage, such that

$$V_0 = \frac{Q}{C}$$

where C is the capacitance between electrodes. Further more

$$C = \epsilon_0 \epsilon_r \frac{A}{t} \text{ farads}$$

Combining the above equations, we obtain :

$$\begin{aligned} V_0 &= \frac{K}{\epsilon_0 \epsilon_r} t \frac{F}{A} \\ &= g t P \end{aligned}$$

where g is the crystal voltage sensitivity in Vm/N and P is the applied pressure in N/m<sup>2</sup>.

There are two main groups of piezo-electric crystals: (i) natural crystals such as quartz and tourmaline, b) synthetic crystals such as Rochelle salts, lithium sulphate (LS), ammonia hydrogen phosphate (ADP), ethylene diamine tartrate (EDT), potassium tartrate (DKT) etc. The advantages vary from crystal to crystal and one is chosen on the basis of a particular application. Tourmaline is the least active chemically while tartaric acid is most active electrically.

iv. **Natural crystals** have a very low electrical leakage when used with very high input impedance amplifiers and permit the measurement of a slowly varying parameter. They are, therefore, capable of withstanding higher temperatures; operating at low frequencies and sustaining shocks.

v. **Synthetic crystals** exhibit a much high output for an applied stress and are about thousand times more sensitive than natural crystals. However, they are usually unable to withstand high mechanical strain

without fracture. Further, the synthetic crystals have an accelerated rate of deterioration over the natural ones.

The major advantages of piezoelectric transducers are:

- 2 High frequency response,
- 3 High output,
- 4 Rugged construction
- 5 Negligible phase shift, and
- 6 Small size. The small size of the transducer is especially useful for accelerometers where added mass will mechanically load a system.

**Applications:** Piezo-electric transducers are most often used for accelerometers, pressure cells and force cells in that order.

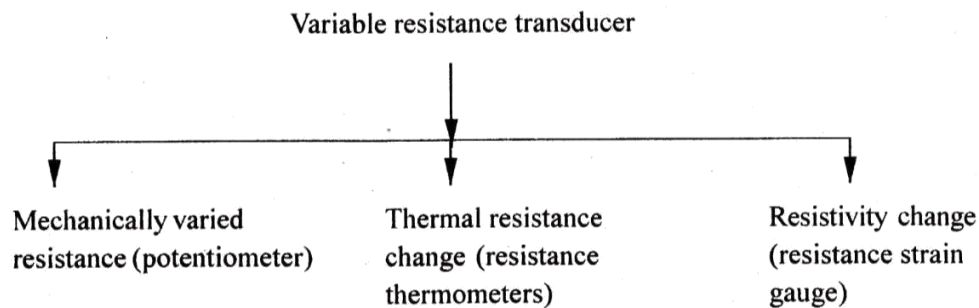


### Resistance Transducers:-

#### Variable resistance transducers:-

In terms of physical quantities, the equation for electrical resistance of a metal conductor is

where  $R$  is the resistance (ohms),  $\rho$  is the conductor resistivity or specific resistance (ohm cm),  $l$  is the physical length (cm) and  $A$  is the uniform cross sectional area of the resistor (cm<sup>2</sup>). Any method of varying one of these quantities can be the design basis of an electrical transducer. In the variable resistance transducer, an indication of measured physical quantity is given by a change in the resistance.



Further, with some devices resistance changes with light intensity (photo conductive effect) while with others the resistance changes on exposure to magnetic field (magneto resistive effect).

The variable resistance transducers are active, and they rely on an external excitation voltage for their operation. However, they are straight forward in design, simple and easy to use.

**Linear and angular motion potentiometers :** These potentiometers convert the linear motion (or the angular motion of a rotating shaft) into changes in resistance. Basically a resistive potentiometer (or 'pot.') is a variable resistor whose resistance is varied by the movement of a slider over a resistance element. (Fig 4.2, a.b). Translatory devices have strokes from 2 mm to 50 cm, while rotational ones have a full scale ranging from  $10^\circ$  to as much 60 full turns.

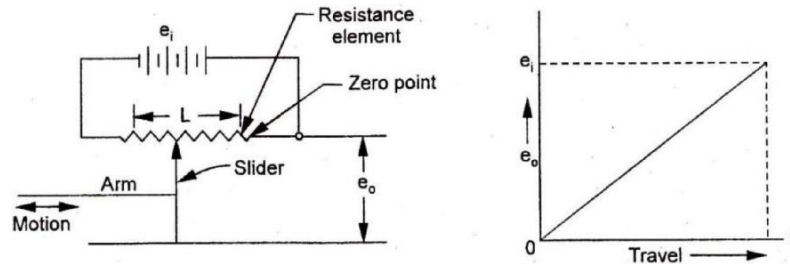


Fig. 4.2.(a) Linear motion potentiometer schematics

The resistance elements in common use are wire wound because that gives sufficiently high resistance value in small space. The characteristics of the resistance wire are :

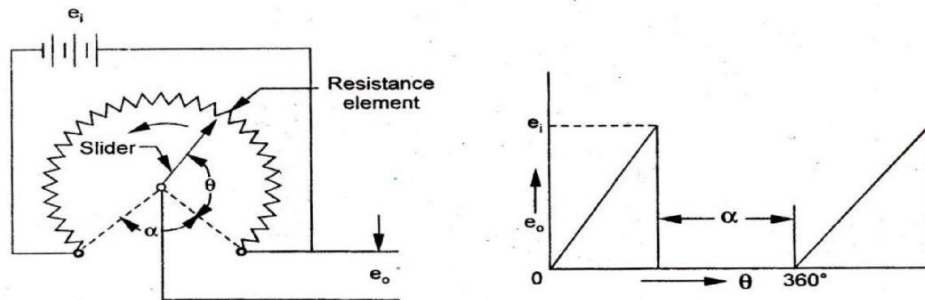


Fig. 4.2 (b) Rotary motion potentiometer schematics

- precision drawn wire with a diameter of about 25 to 50 microns, and wound over a cylindrical or a flat mandrel of ceramic, glass, anodized aluminium.
- resistivity of wire ranges from  $0.4 \mu\Omega\text{-m}$  to  $1\text{-}3 \mu\Omega\text{-m}$ , and temperature coefficient varies from 0.002% per  $^\circ\text{C}$  to 0.001% per  $^\circ\text{C}$ . With these values, the device operates with appreciable constant sensitivity over a wide temperature range.
- the wire is strong, ductile, and protected from surface corrosion by enamelling or oxidation. The materials commonly employed are the alloys of copper-nickel, nickel-chromium, and silver-palladium,

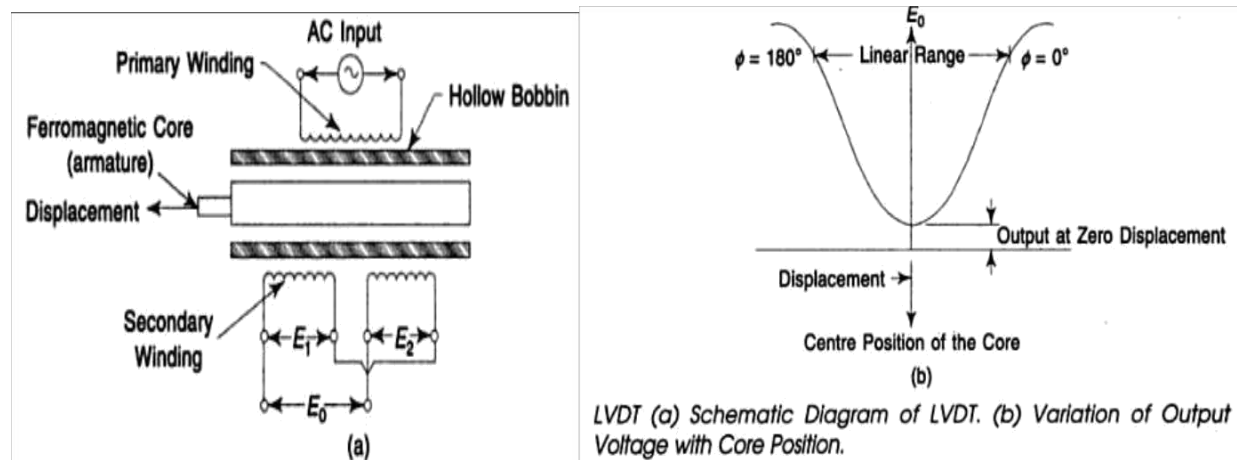
#### Variable inductance transducers:-

- (b) LVDT (Linear variable differential Transducer)
- (c) RVDT (Rotary variable differential Transducer)
- (d) Synchros
- (e) Resolvers

## 1. LVDT (Linear variable differential Transducer):

The linear variable-differential transformer (LVDT) is the most widely used inductive transducer to translate linear motion into electrical signal.

**Construction:** A differential transformer consists of a primary winding and two secondary windings. The windings are arranged concentrically and next to each other. They are wound over a hollow bobbin which is usually of a non-magnetic and insulating material, as shown in Fig.



**Working:** Any physical displacement of the core causes the voltage of one secondary winding to increase while simultaneously, reducing the voltage in the other secondary winding. The difference of the two voltages appears across the output terminals of the transducer and gives a measure of the physical position of the core and hence the displacement.

When the core is in the neutral or zero position, voltages induced in the secondary windings are equal and opposite and the net output is negligible. As the core is moved in one direction from the null position, the differential voltage, i.e. the difference of the secondary voltages, will increase while maintaining an in-phase relationship with the voltage from the input source. In the other direction from the null position, the differential voltage will again increase, but will be  $180^\circ$  out of phase with the voltage from the input source. By comparing the magnitude and phase of the output (differential) voltage with the input source. The amount and direction of movement of the core and hence of displacement may be determined. Variation of output voltage with core position is shown in Fig.

### Following are the advantages of LVDT:

4. The output voltage of these transducer is practically linear for displacements upto 5 mm.
5. They have infinite resolution.
6. These transducers possess a high sensitivity.
7. These transducers can usually tolerate a high degree of shock and vibration without any adverse effects.
8. They are simple, light in weight, and easy to align and maintain.

**Following are the disadvantages of LVDT:**

- 2 Relatively large displacements are required for appreciable differential output.
- 3 They are sensitive to stray magnetic fields but shielding is possible.
- 4 They are inherently low in power output.

## **2. RVDT (Rotary variable differential Transducer):**

A RVDT is used to convert rectangular displacement into electrical signal. The construction and working of RVDT is same as that of LVDT except that it employs a cam shaped core. This core rotates between the primary and two secondary windings with the help of shaft.

## **3. Synchros:**

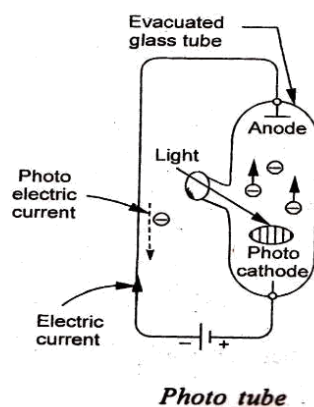
The devices by which the angular position of shaft is converted into electrical signal are known as synchros. The synchros are electromagnetic transducers. The construction of synchro is same as a three phase alternator. It has a stator and a rotor. The stator consists of 3 identical stationary windings which are separated by  $120^\circ$  in space. These stationary windings are connected in star (Y) configuration.

The rotor is dumb-bell shaped rotor to which an AC excitation voltage is applied through slip rings. The rotor acts as primary winding of single phase transformer where as the stationary windings act as secondary winding of single phase transformer. There are two basic parts in a synchro system namely synchro transmitter and synchro receiver.

## **4. Resolvers:**

It is an electromagnetic device which consists of two stator windings and two rotor windings. Resolving is nothing but converting from one co-ordinate system to another coordinate system. The resolver converts the shaft's angular position into Cartesian coordinates i.e., the angular rotor position is converted into those signals which are proportional to the sine and cosine of the rotor position and this is carried out with respect to the position of the stators.

## **Photo-electric Transducers:-**

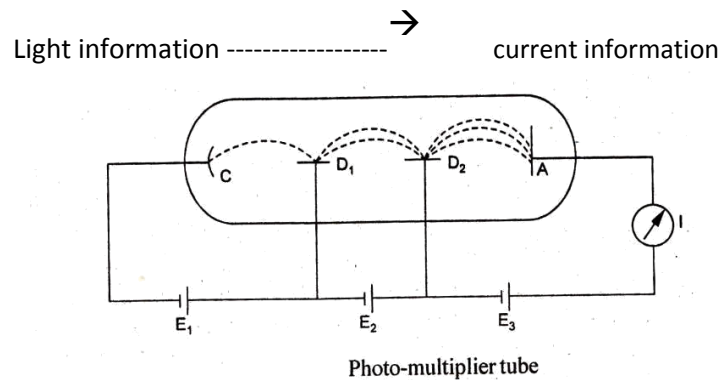


These transducers operate on the principle that when light strikes special combination of materials, a voltage may be generated, a resistance change may take place, or electrons may flow. Photoelectric

cells are used for a wide variety of purposes in control engineering for precision measuring devices, in exposure meters used in photography. They are also used in solar batteries as sources of electrical power for rockets and satellites used in space research.

Based on the principle of rotation photo electric transducers are classified into the 3 types. They are,

**3. Photo-emissive cell:** These transducers operate on the photo-emissive effect, i.e., when certain types of materials are exposed to light, electrons are emitted and a current flow is produced. Light sensitive photo-cathode may consist of a very thin film of cesium deposited by isotonic onto an oxidised silver base. Light strikes the cathode, causing the emission of electrons which are attracted towards the anode. This phenomenon produces flow of current in the external circuit; the current being a function of radiant energy striking the cathode.



**b Photo-conductive cell:** These are the variable resistance transducers. They operate on the principle of photoconductive effect, i.e., some special type of semiconductor materials change their resistance when exposed to light.

Light information -----> resistance information

Figure shows schematically the construction and electrical circuit of a photoconductive cell. The sensitive material usually employed is cadmium selenide, germanium etc in the form of thin coating between the two electrodes on a glass. Further, the cells are used in the circuit as a variable resistance and are put in series with an ammeter and a voltage source. When the light strikes the semiconductor material, there is a decrease in the cell resistance thereby producing an increase in the current indicated by the ammeter.

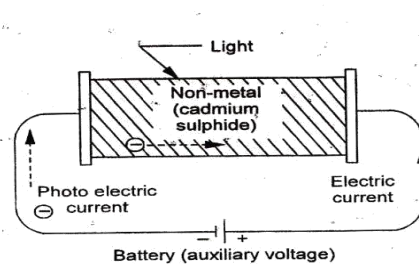


Fig. Photo-conductive cell

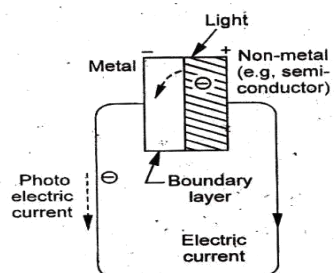


Fig. Photo-voltaic cell



**d. Photo-voltaic cell:** These transducers operate on the photo-voltaic effect, i.e., when light strikes a junction of certain dissimilar metals, a potential difference is built up.

Light information -----> emf information

The cell consists of a metal base plate, a non-metal semiconductor and a thin transparent metallic layer. Typical examples of the layers are the copper oxide on copper and iron oxide on iron combination. The transparent layer may be in the form of a sprayed conducting lacquer. Light strikes the coating and generates an electric potential. The output is, however, low and is non-linear function of the light intensity. In contrasted photo-tube and photo-conductive cells, the photo-voltaic unit is self-generating, rated and requires no voltage source to operate it.



#### Capacitive Transducers:-

### **Capacitive transducers**

A capacitor comprises two or more metal plate conductors separated by an insulator. As voltage is applied across the plates, equal and opposite electric charges are generated on the plates. Capacitance is defined as the ratio of the charges to the applied voltage and for a parallel plate capacitor is given by :

$$C = \epsilon_0 \epsilon_r \frac{A}{t} (N - 1) \text{ farads}$$

where  $A$  = overlapping or effective area between plates ( $\text{m}^2$ ),

$t$  = distance between plates (m),

$N$  = number of capacitor plates,

$\epsilon_0$  = permittivity of free space =  $8.854 \times 10^{-12}$  F/m

$\epsilon_r$  = relative permittivity (or dielectric constant) of the material between the plates.

The value of  $\epsilon_r$  depends upon the insulator material and for air  $\epsilon_r = 1$

For a cylindrical capacitor, the capacitance is

$$C = \epsilon_0 \epsilon_r \frac{2\pi l}{\log_e \left( \frac{r_2}{r_1} \right)} \text{ farads} \quad \dots(4.10)$$

where

$l$  = length of overlapping part of cylinders (m),

$r_1$  = radius of inner cylindrical conductor (m),

$r_2$  = radius of outer cylindrical conductor (m).

A capacitive pick up operates on the principle of a variation in capacitance produced by the physical quantity being measured. The capacitance can be made to vary by changing either the relative permittivity (dielectric constant)  $\epsilon_r$ , the effective area  $A$ , or the distance between the plates  $t$ . The mechanical displacement is generally measured by noting the change in capacitance brought about by either change in area or by change in distance between the plates. The change in dielectric is used to measure changes in liquid or gas levels.

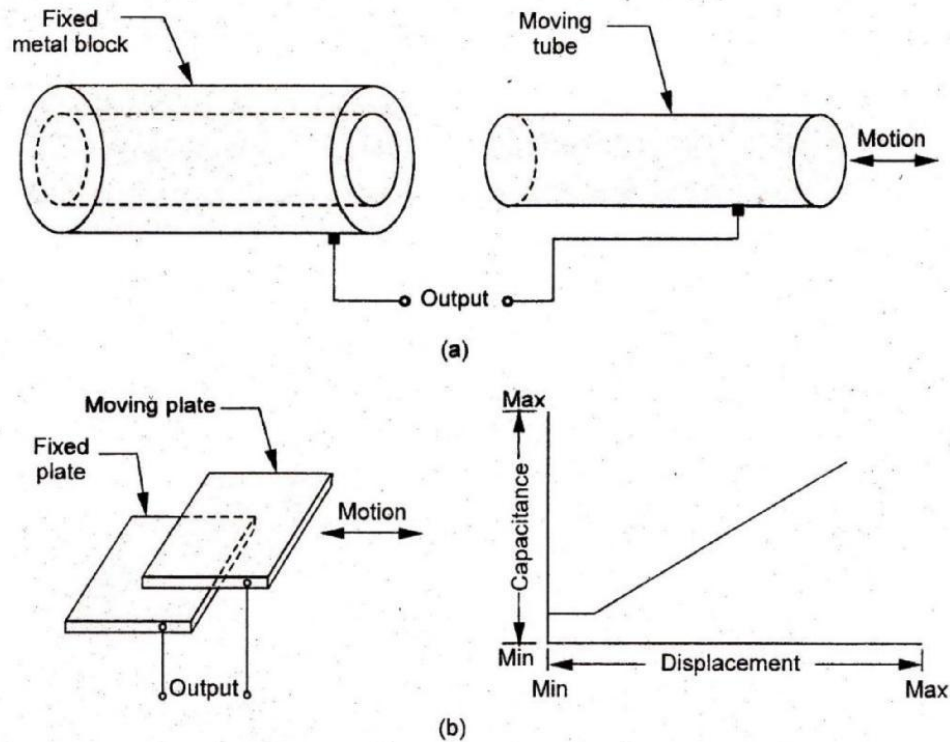


Fig. 4.12 Capacitance transducer: area change

Fig. 4.12 represents the elementary diagrams of the two arrangements of a capacitance transducer where capacitance change occurs because of change in the area of plates. Since capacitance is directly proportional to the effective area of the plates, response of such a system is linear.

Fig. 4.13 represents the basic form of a capacitance transducer utilizing the effect of change of capacitance with changes in distance between the two plates. One is a fixed plate and the displacement to be measured is applied to the other plate which is moving. Since capacitance varies inversely as the distance between the plates, the response of this transducer is not linear.

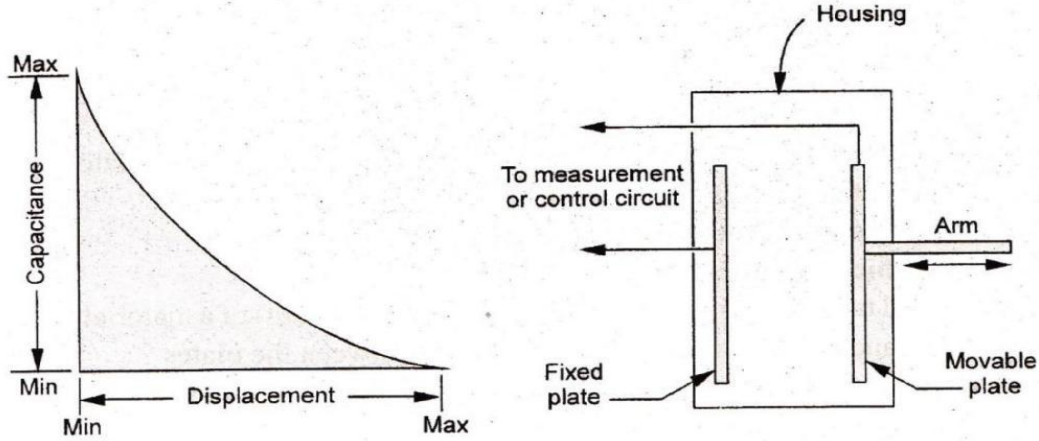


Fig. 4.13 Capacitance transducer : change in distance between the plates

In a differential capacitor, let the normal position of the central plate be represented by a line as shown in Fig. 4.14. The capacitances  $C_1$  and  $C_2$  are then identical, i.e.,

$$C_1 = C_2 = C = \epsilon_0 \epsilon_r \frac{A}{t} \quad \dots(4.11)$$

When the central plate is displaced parallel to itself through a distance  $x$ , the capacitances are :

$$C_1 = \epsilon_0 \epsilon_r \frac{A}{t+x}; \quad C_2 = \epsilon_0 \epsilon_r \frac{A}{t-x} \quad \dots(4.12)$$

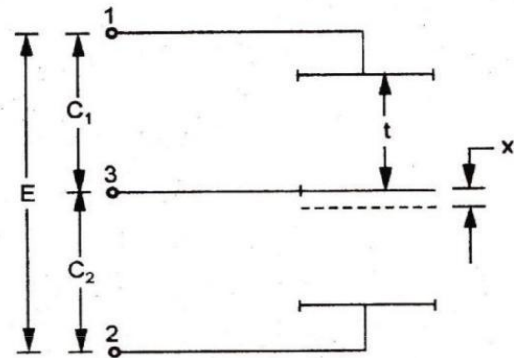


Fig. 4.14 Differential capacitor system

For an alternating voltage  $E$  applied between the terminals 1 and 2, the voltages across  $C_1$  and  $C_2$  are given by :

$$E_1 = \frac{E C_2}{C_1 + C_2} = E \frac{t+x}{2t} \quad \dots(4.13)$$

and

$$E_2 = \frac{E C_1}{C_1 + C_2} = E \frac{t-x}{2t} \quad \dots(4.14)$$

When the output from the terminal pairs 1 and 3, and 2 and 3 is fed into a differential measurement circuit, the voltage difference would be recorded.

$$E_1 - E_2 = E \frac{x}{t} \quad \dots(4.15)$$

The voltage difference is a linear function of the displacement of the middle plate.

## **UNIT-II**

### **Measurement of Temperature**

Temperature is probably, most widely measured and frequently controlled variable encountered in industrial processing of all kinds measurement of temperature is involved in thermo dynamics, heat transfer and many chemical operations. Basically all the properties of matter such as size, colour, electrical and magnetic characteristics and the physical states (solid, liquid, gas) change with changing temperature.

#### **Definition:**

Temperature may be defined as the degree of hotness and coldness of a body are an environmental measured on a definite scale.

The temperature of a substance is a measure of the hotness, or coldness, of that substance. It is the thermal site of a body or a substance which determines whether it will give heat to, or receive heat from, other bodies. If two bodies are placed in contact then heat tends to flow from a body at a higher temperature to a body at a lower temperature, just as water flows from higher to lower levels.

The terms, heat and temperature, are closely related Temperature may be defined as "degree of heat" but heat is usually taken to mean "quantity of heat" Temperature and heat flow are related quantitatively by the second law of thermodynamics, which states that heat flows. Of its own accord, from a body at a higher temperature to a body at a lower temperature. It is therefore important to remember that in temperature measurement, two bodies in intimate contact are at the same temperature only if there is no heat flow between them.

#### **Temperature scales:**

Temperature scales are based upon some recognized fixed points. At least two fixed points are required which are constant in temperature and can be easily reproduced as:

##### **(i) Centigrade and fahrenheit heat scales:**

On both these scales the freezing point and boiling point of water are used as fixed point. The freezing point. The centigrade scale abbreviated as  $^{\circ}\text{C}$ , assigns  $0^{\circ}\text{C}$  to the ice point and  $100^{\circ}\text{C}$  to the steam point and the intervals between these points is divided into 100 equal points. The corresponding values of the Fahrenheit scale deviated  $^{\circ}\text{F}$  are  $32^{\circ}\text{F}$  and  $212^{\circ}\text{F}$  with the interval divided into 180 equal parts.

##### **(ii) kelvin and rankine absolute scales:-**

On the kelvin and rankine scales the absolute and hypothetically placed at  $-273.2^{\circ}$  and  $-459.7^{\circ}$  .

##### **(iii) Thermo dynamic scale:-**

The efficiency of an ideal engine operating up on the control cycle between any two temperatures is given by

#### **4. International temperature scale:-**

This scale has been established and adopted provide an experimental basis for the calibration of specific thermometers to indicate temperatures as close as possible to the Kelvin thermodynamic scale. The International temperature scale covers the range from the boiling point of oxygen to the highest temperatures of incandescent bodies and names. The main features of this scale, adopted in 1948 at the Ninth General Conference on Weights and Measures are:

4. Temperatures are to be designated as of and denoted by the symbol t. The name Celsius was officially adopted to replace the name Centigrade.
5. The scale is based upon a number of fixed and reproducible equilibrium temperatures to which numerical values are assigned.

#### **Fundamental fixed points and their numerical values (at standard atmospheric pressure of 1013250 dynes/ )**

FIXED POINT	TEMPERATURE°C
1.Temperature of equilibrium between liquid oxygen and it's vapour (oxygen point)	-182.97
2 .Temperature of equilibrium between ice and (saturated) water (ice point) fundamental fixed point.	0
3. Temperature of equilibrium between liquid, water and it's vapour (steam point)-fundamental fixed point.	100
4. Temperature of equilibrium between liquid, sulphur and it's vapour (sulphur point)	444.60
5.Temperature of equilibrium between solid and liquid silver(silver point)	960.8
6. Temperature of equilibrium between the solid and liquid gold (gold point)	1063

#### **Classification:-**

The instruments for measuring temperature have been classified in the first place according to the nature of change produced in the testing body by the change of temperature. The following four broad categories have been proposed.

- iv.Expansion thermometers.
- v. Change of state thermometer.
- vi.Electrical methods of measuring temperature.

4. Radiation and optical pyrometer.

**e) EXPANSION THERMO METERS:-**

(a)Expansion of solids

Bimetallic thermometer

Solid rod thermometer

Expansion of liquids

liquid in glass thermometer

liquid in metal thermometer

(C) Expansion of gases-gas thermometer

**f) Change of state thermometers:-**

Liquid in metal thermometers (or) vapour pressure thermometers.

**5. Electrical methods of measuring temperature:-**

Electrical resistances bulbs.

Thermistors.

Thermo couples and thermopiles.

**6. Radiation and optical pyrometers:-**

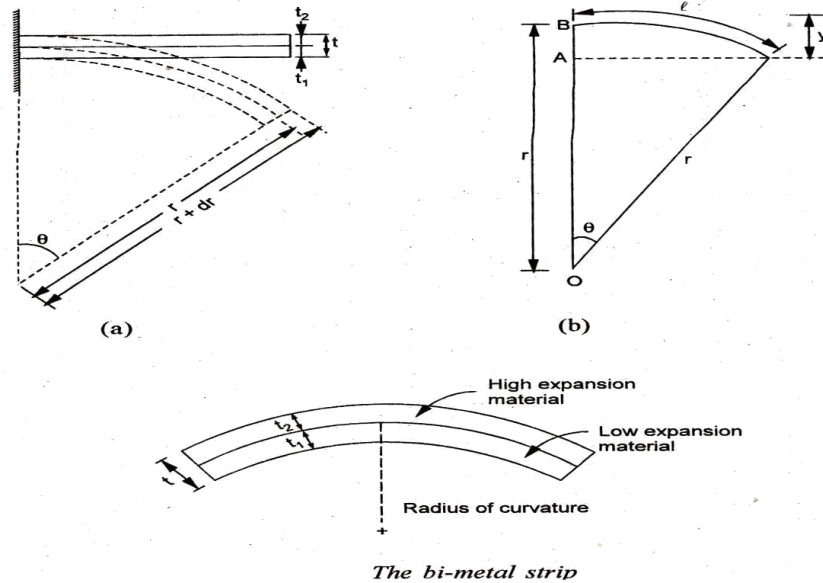
Optical pyrometers (total radiation pyrometer).

**Ranges:-**

Type	Range°C	Accuracy°C
1.Glass thermometers		
(a) mercury filled	-39 to 400	0.3 to 1.0
(b) alcohol filled	-39 TO 540	0.3 TO 5.5
(C) Alcohol filled	-70 to 65	0.5 to 1.0
2.Pressure gauge thermometer.		
(a) vapour pressure type	11 to 200	1 to 5.5
(b) liquid (or) gas type filled	-150 to 600	1 to 5.5
3.Bimetallic thermometer	-74 to 540	0.3 to 14.0
4.Resistance thermometer	-240 to 980	0.003 to 3.0
5.Thermo couples		
(a) base metals	-185 to 1150	0.3 to 11.0
(b) Precious metals	-185 to 1150	0.3 to 11.0
6.Thermistors	-100 to 260	Depends up on ageing
7.pyrometers		
(a) optical	760 and above	11 for black body
(b) radiation	540 and above	11-16 for black body

8.fusion	590 to 3600	As low as 20-30 under optimum conditions.
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### Bimetallic thermometer:- (or) solid expansion:-



### **Construction:-**

A bimetallic strip consists of two pieces of different materials firmly bonded together by bending. For a bi-metal in the form of a straight cantilever beam temp changes cause the free end to deflect because of the different expansion rates of the components. This deflection can be correlated quantitatively to the temp change.

The radius of curvature of the bend of a straight bi-metal beam may be calculated as

$$r = t \frac{[3(1+m)^2 + (1+mn)(m^2 + 1/mn)]}{6(\alpha_2 - \alpha_1)(T - T_0)(1+m)^2}$$

where  $t$  is combined thickness of the bonded strip,  $(t_1 + t_2)$

$m$  is the ratio of thickness of low to high expansion materials,  $t_1 / t_2$

$n$  is the ratio of moduli of elasticity of low to high expansion material,  $E_1 / E_2$

$\alpha_1$  is lower coefficient of expansion

$\alpha_2$  is higher coefficient of expansion

$T$  is operating temperature

$T_0$  is initial bonding temperature

If  $t_1 = t_2$  and if the materials are so chosen that  $E_1 \approx E_2$ , equation 10.11 simplifies to

$$r = \frac{2t}{3(\alpha_2 - \alpha_1)(T - T_0)}$$



Normally the two expansion material is invar and the high expansion material is brass. The respective coefficient of expansion for invar and brass.

The respective coefficients of expansion for invar and brass are  $0.009 \times 10^{-4}$  per  $^{\circ}\text{C}$  and  $0.189 \times 10^{-4}$  per  $^{\circ}\text{C}$ .

When bimetallic strip in the form of cantilever is assumed to bend to a circular arc then

$$\frac{r + dr}{r} = \frac{\text{expanded length of strip having higher expansion coefficient}}{\text{expanded length of strip having lower expansion coefficient}}$$

$$= \frac{l[1 + \alpha_2 (T - T_0)]}{l[1 + \alpha_1 (T - T_0)]}$$

Simplification gives

$$r = \frac{dr [1 + \alpha_1 (T - T_0)]}{(\alpha_2 - \alpha_1) (T - T_0)}$$

With the low expansion metal of invar and the thickness of each metal strip  $t/2$ ,

$$\alpha_1 \approx 0 \quad \text{and} \quad dr = t/2$$

With these stipulations, equation 10.13 reduces to

$$r = \frac{t}{2 \alpha_2 (T - T_0)}$$

Bimetallic elements can be arranged in the flat spiral the single helix and the multiple helix configuration.

#### Characteristics:-

- 6) Low cost.
- 7) Simple and compact

#### Applications:-

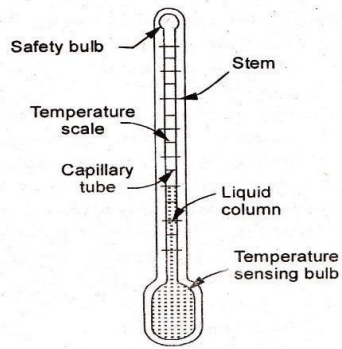
- 4) Control of gas flow
- 5) electric iron boxes
- 6) Domestic ovens.

#### Liquid in glass thermometers:-

The liquid in glass thermometers is one of the most common types of temp measuring devices. The unit consists of glass envelope, responsive liquid and indicating scale.

Liquid	range $^{\circ}\text{C}$
Mercury	-3.5 to 510
Alcohol	-80 to 70
Toluene	-80 to 100
Pentane	-200 to 30
Creosote	-5 to 200





*Liquid-in-glass thermometer*

The choice in the type of economics influenced by the range of the thermometer. Higher the range, higher the cost. For temperature up to 450 °C normal glass is used. At high temp up to 550°C. Above this temp quartz thermometers have been used.

### **Salient features/characteristics:-**

- ☐ Low cost and simplicity of use
- ☐ Portable
- ☐ Ease of checking for physical damage
- ☐ Absence of need for auxiliary instruments.
- ☐ No need of additional indicating instruments

☐ Range limited to about 600°C.

### **Calibration of liquid in glass thermometer:-**

7) Complete immersion

8) Total immersion

9) Partial immersion

$$\text{Correction factor} = 0.00018N(T_1 - T_2)$$

= Stem Correction In Degrees To Be Added algebraically To The Indicated Temp

N = Number of degrees of exposed

T<sub>1</sub> = Reading of the primary thermometer and

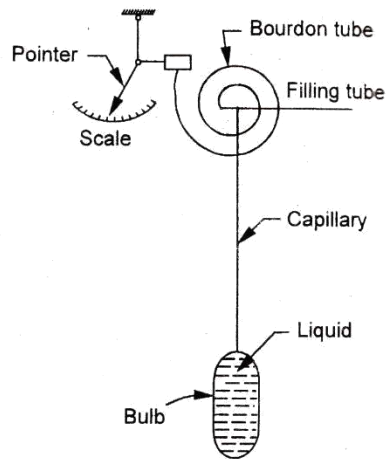
T<sub>2</sub> = Average temperature of exposed stem.

### **Liquid in metal thermometers:-**

The two distinct disadvantages of liquid in glass thermometers are

1. The glass is very fragile and hence care should be taken in handling these thermometers.

- 2 The position of the thermometer for accurate temp measurement is not always the best position for reading the scale of the thermometer



*Filled-system thermometer*

Both of these disadvantages are overcome in mercury in steel thermometer. The principle of operation is again the differential expansion of liquid which is used.

- d) a temperature sensitive element (bulb) filled with expanding fluid
- e) a flexible capillary tube
- i. a pressure or volume sensitive device such as Bourdon tube, bellows or diaphragms, and
- ii. a device for indicating or recording a signal related to the measured temperature.

#### **Advantages and limitations :**

- iv. Simple and inexpensive design of the system
- v. Quite rugged construction, minimum possibility of, damage or failure in shipment, installation and use
- vi. Fairly good response, accuracy and sensitivity
- vii. Remote indication upto about 100 m possible with capillary lines.

#### **Gas Thermometer:-**

This system is defined as "a thermal system with a gas and operating on the principle of pressure change with temperature change". The expansion, of a gas is governed by the ideal gas law:

$$PV = RT; P = (RT/V)$$

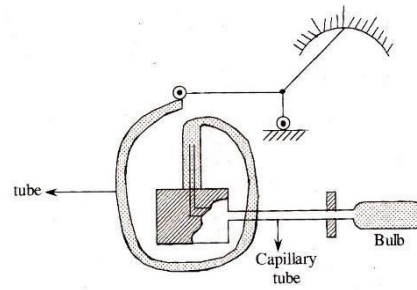


Figure: Gas Thermometer

Gas: Nitrogen gas

Range: -130° to 540°

The volume of gas required in the bulb is determined by the gas expansion and by the temperature range of the instrument.

$$V = R \left( \frac{P_1}{P_2} \right)$$

Where subscripts 1, 2 refer to the conditions at the lowest and highest points of the scale.

✓

### Electrical Methods:-

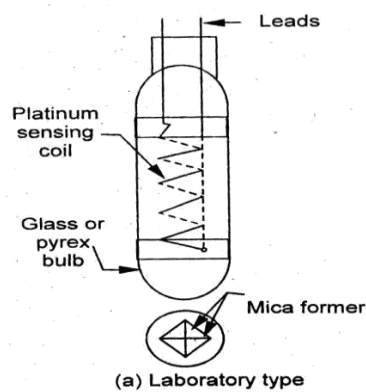
In electrical methods of measuring temperature, the temperature signal is converted into electrical signal either through a change in resistance or voltage development of emf.

7) Resistance Thermometers

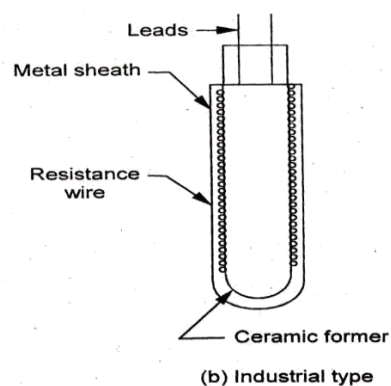
8) Thermistors

9) Thermo couples

### **1. Resistance Thermometers:**



(a) Laboratory type



(b) Industrial type

Resistance thermometers

The resistance  $R$  (ohms) of an electrical conductor of resistivity  $\rho$  (ohms.c), length  $L$  (cm) and cross sectional area  $A$  (cm<sup>2</sup>) is given by

$$R = \rho L/A$$

As temperature changes, the resistance of the conductor also changes. This is due to two factors : (i) dimensional change due to expansion or contraction and (ii) change in the current opposing properties of the material itself. For an unconstrained conductor, the latter is much more than 99% of the total change for copper. This change in resistance with temperature is used for measuring temperature.

Most metals become more resistant to the passage of electric current as they become hotter, i.e., their resistance increases with growth in temperature. An adequate approximation of the resistance-temperature relationship is given by :

$$R_t = R_0 (1 + \alpha t + \beta t^2) \quad \dots(10.25)$$

where  $R_t$  is resistance at any temperature  $t$  °C,  $R_0$  is resistance at zero °C,  $\alpha$  and  $\beta$  are constants depending on the material. The constants  $R_0$ ,  $\alpha$  and  $\beta$  are determined at the ice, steam and sulphur points respectively. For platinum resistance thermometer,  $R_t / R_0$  must not be less than 1.39 for  $t = 100$  °C to indicate the purity of the metal and the stability.

Over a limited temperature range around zero °C, the following linear relationship is equally valid :

$$R_t = R_0 (1 + \alpha \theta_t)$$

The thermometer comprises a resistance element or bulb, suitable electrical leads and an indicating - recording or resistance measuring instrument. The resistance element is, usually in the form of a coil of very fine platinum, nickel or copper wound non-conductively. Onto an insulating ceramic former which is protected externally by a metal sheath. A laboratory type of resistance thermometer is often wound on a crossed mica former and enclosed in a pyrex tube. The tube may be evacuated or filled with an inert gas to protect the metal wire. Care is to be taken to ensure that the resistance wire is free from mechanical stresses. A metal which has been strained will suffer a change in the resistance characteristics; the metal is therefore usually annealed at a temperature higher than that at which it is so operate.

Platinum is preferred because,

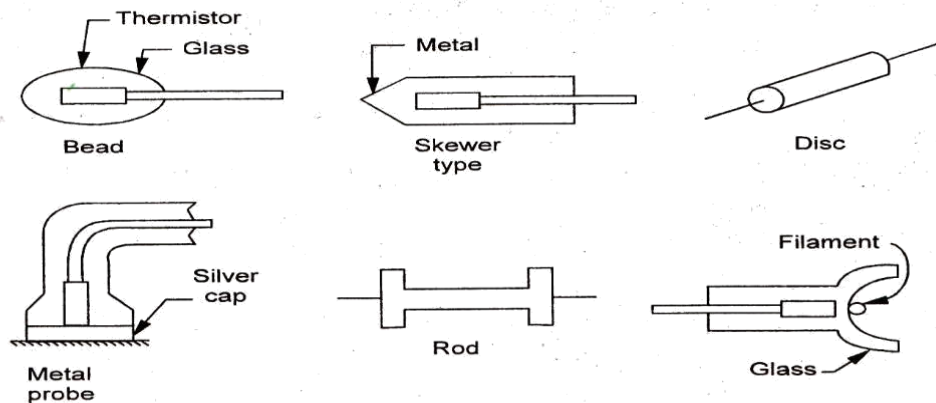
- 4) Physically stable (i.e., relatively indifferent to its environment, resists corrosion and chemical attack and is not readily oxidised) and has high electrical resistance characteristics.
- 5) Accuracy attainable with a platinum resistance thermometer is of the order of  $\pm 0.01$  of upto 500° and within  $\pm 0.1^\circ$  of upto 1200 ° .

#### **Advantages:-**

- (iv) Simplicity and accuracy of operation
- (v) Possibility of easy installation and replacement of sensitive bulb

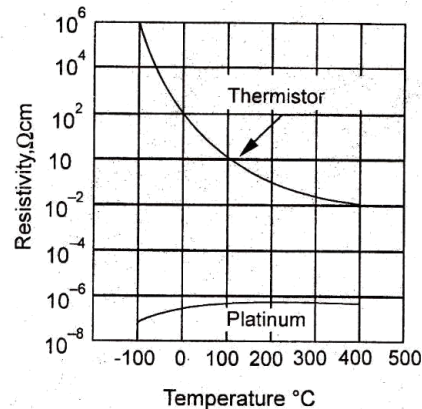
B) Easy check on the accuracy of the measuring circuit 'by substituting a standard resistance for the resistance element.

## 2. Thermistors:



*Typical thermistor forms*

Thermistors is a contraction of term Thermal Resistor. They are essentially semi-conductors which behave as resistors with a high negative temperature coefficient. As -the temperature increases, the resistance goes down, and as the temperature decreases, the resistance goes up. This is just opposite to the effect of temperature changes on metals.



Thermistors are composed of sintered mixture of metallic oxides such as manganese, Nickel, cobalt, copper, iron and uranium. These metallic oxides are milled, mixed in appropriate proportions, are pressed into the desired shape with appropriate binders and finally sintered the electrical terminals are either embedded before sintering or baked afterwards. The electrical characteristics of thermistors are controlled by varying the type of oxide used and physical size and configuration of the thermistor. Thermistors may be shaped in the form of beads, disks, washers, rods and these standard forms are shown in Fig.

The mathematical expression for the relationship between the resistance of a thermistor and absolute temperature of thermistor is

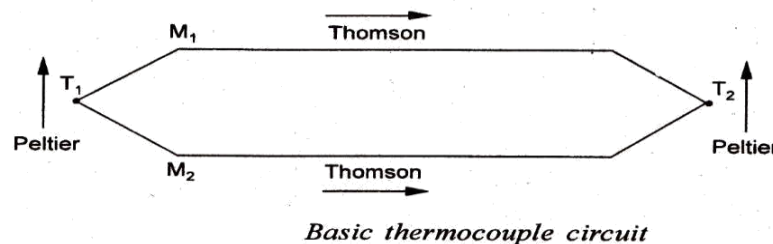
$$R_t = R_o e^{\beta \left( \frac{1}{T} - \frac{1}{T_o} \right)}$$

where  $R_t$  is the resistance at  $T$  °K,  $R_o$  is the resistance at absolute temperature  $T_o$ ,  $\beta$  is constant depending on the thermistors formulation or grade, typical range is (3400 – 4000 °K).

### 3. Thermo couples:

The basic principle of temperature measurement by thermo-electricity was discovered by Seebeck in 1821 and is illustrated in Fig. 10.20. When two conductors of dissimilar metals M1 and M2 are joined together to form a loop (a thermocouple) and two unequal temperatures  $T_1$  and  $T_2$  are imposed at the two interface connections, an electric current we through the loop.

Experimentally it has been found that -the magnitude of the current is directly related to the two materials M1 and M2, and the temperature difference ( $T_1 - T_2$ ). In the practical application of the effect, a suitable device is incorporated in the circuit to indicate any electromotive force or Bower current. For convenience of measurement and standardization, one of the two junctions is usually maintained at some constant known temperature. The output voltage of the circuit then indicates the temperature difference relative to the reference temperature. Most tabulations set the reference value to the triple point of water (0° ).



Thermo-electric effects arise in two ways:

- iii) a potential difference always exists between two dissimilar metals in contact with each other (Peltier effect)
- iv) a potential gradient exists even in a single conductor having a temperature gradient (Thomson effect)

In commercial instruments, the thermocouple materials are so chosen that the Peltier and Thomson emfs act in such a manner that the combined value is maximum and that varies directly with temperature.

**Elements of a thermo-electric pyrometer :** The essential elements of a thermo-electrical pyrometer are shown schematically in Fig.

- \* Two dissimilar conductors electrically insulated except at the hot junction, where the conductors may either be soldered or welded together, or may be completely separated from each other.

### **Measurement of pressure:**

#### **Pressure definition:-**

The action of force against some opposite force.

OR

A force in the nature of thrust distributed over a surface.

OR

The force acting against a surface within a closed container.

#### **Units:-**

Some of the commonly used pressure units are:

$1 \text{ bar} = 10^5 \text{ N/m}^2 = 1.0197 \text{ kgf/cm}^2 = 750.06 \text{ mm of Hg.}$   
 $1 \text{ micron} = 1 \text{ M} = 10^{-3} \text{ mm of Hg.}$

$1 \text{ torr} = 1 \text{ mm of Hg.}$

$1 \text{ bar} = 1 \text{ dyne/cm}^2$

$\text{Pa} = \text{N/m}^2$

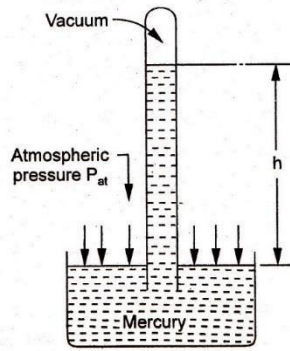
#### **Terminology:-**

Following terms are generally associated with pressure and its measurement.

#### **Atmospheric pressure ( ):-**

This is the pressure exerted by the envelope of air surrounding the earth surface. Atmospheric pressure is usually determined by a mercury column barometer shown in fig. A long clean thick glass tube closed at one end is filled with pure mercury. The tube diameter is such that capillary effects are minimum. The open end is stoppered and the tube is inserted into a mercury container; the stoppered end kept well beneath the mercury surface. When the stopper is removed, mercury runs out of the tube into the

container and eventually mercury level in the tube settles at height  $h$  above mercury level in the container. Atmospheric pressure acts at the mercury surface in the container, and the mercury vapour pressure exits at the top of mercury column in the tube. From hydrostatic equation,  $p = p_0 + \rho gh$  (i)



*Simple barometer*

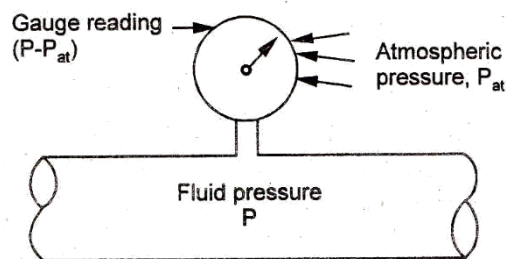
Mercury has a low vapour pressure ( $\approx 1.6 \times 10^{-6}$  bar at  $20^\circ\text{C}$ ) and thus for all intents and purposes it can be neglected in comparison to which is about 1.0 bar at mean sea level. Then

Atmospheric pressure varies with altitude, because the air nearer the earth's surface is compressed by air above. At sea level, value of atmospheric pressure is close to 1.01325 bar or 760 mm of Hg column (= 10.33 m of water column).

**Absolute pressure ( ):-**

It is defined as the force per unit area due to the interaction of fluid particles amongst themselves. A zero pressure intensity will occur when molecular momentum is zero. Such a situation can occur only when there is a perfect vacuum, i.e., a vanishingly small population of gas molecules or of molecular velocity. Pressure intensity measured from this state of vacuum or zero pressure is called absolute pressure.

**GAUGE PRESSURE ( ) AND VACUUM PRESSURE ( ):-**



*Gauge pressure*

Instruments and gauges used to measure fluid pressure generally measures the difference between the unknown pressure 'P' and the existing atmospheric pressure ''. When the unknown pressure is more than the atmospheric pressure the pressure is recorded by the instrument is called gauge pressure ( ). A pressure reading below the atmospheric pressure is known as vacuum pressure or negative

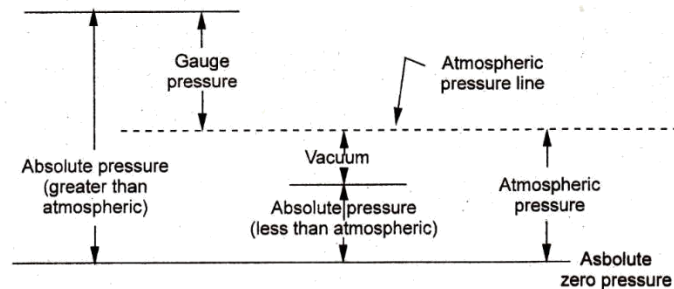


pressure. Actual absolute pressure is the sum of gauge pressure indication and the atmospheric pressure.

$$= \quad +$$

$$= \quad -$$

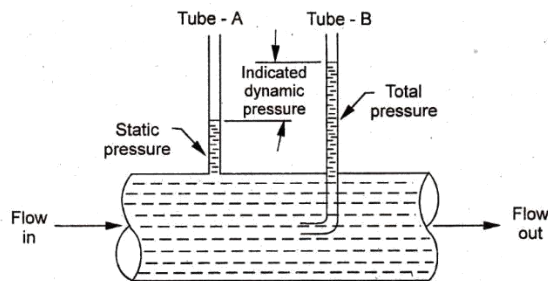
Relation between these pressure terms is illustrated in Fig.



*Relation between absolute, gauge and atmospheric pressure*

### STATIC PRESSURE ( ) AND TOTAL PRESSURE ( ):-

Static pressure is defined as the force per unit area acting on a wall by a fluid at rest or flowing parallel to the wall in a pipe line.



*Static and total pressure*

Static pressure of a moving fluid is measured with an instrument which is at rest relative to the fluid. The instrument should theoretically move with same speed as that of the fluid particle itself. As it is not possible to move a pressure transducer along in a flowing fluid; static pressure is measured by inserting a tube into the pipe line at right angles to the flow path. Care is taken to ensure that the tube does not protrude into the pipe line and cause errors due to impact and eddy formation. When the tube protrudes into the stream, there would be local speeding up of the flow due to its deflection around the tube; hence an erroneous reading of the static pressure would be observed.

Velocity pressure = total pressure – static pressure.

$$\frac{\rho V^2}{2} = \left( \quad - \quad \right)$$

### **Pressure measurement groups:-**

A. Instruments for measuring low pressure (below 1 mm of Hg): - manometers and low pressure gauges.

B. Instruments for medium and low pressures (below 1 mm of Hg to 1000 atmospheres):- Bourdon tube and diaphragm gauges.

C. Instruments for measuring low vacuum and ultra high vacuum (760 torr to  $10^{-9}$  torr and beyond):- McLeod thermal conductivity and ionization gauges.

D. Instruments for measuring very high pressure (1000 atmospheres and above):- bourdon tube, diaphragm and electrical resistance pressure gauges.

E. Instruments for measuring varying pressure:- engine Indicator and CRO ( cathode ray oscilloscope).

### **Classification of pressure measuring devices:-**

3. Gravitational transducer.  
A dead weight tester.  
Manometer.
4. Electrical transducers.  
Bourdon tube pressure gauges.  
Elastic diaphragm pressure.  
Bellows gauges.
5. Strain gauge pressure cells.  
Pinched tubes.  
Cylindrical tube pressure cell.
6. McLeod gauge.
7. Thermal conductivity gauges.  
Thermocouple gauge  
Pirani gauge
8. Ionization gauge.
9. Electrical resistance pressure gauge.

### **VARIOUS PRINCIPLES OF MEASUREMENT:-**

6. Pressure can be measured by balancing a column of liquid against the pressure which has to be measured. The height of the column which is balanced becomes a measure of the applied pressure when calibrated.

Ex: - manometer.

vii. When the pressure is applied to the elastic elements the shape of the elastic element changes which intern the pointer moves with respect to the scale. The pointer readings become a measure of applied pressure.

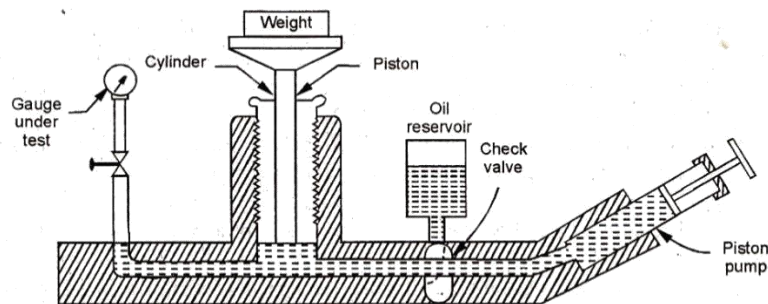
Ex: - bourdon tube pressure gauge, diaphragm, bellows.

g) When electric current flows through a conducting wire it gets heated. Depending up on the conductivity of the surrounding media the heat is dissipated from the wire. The rate of change in the temperature of the wire becomes a measure of the pressure.

Ex:- Pirani gauge, ionization gauge, thermal conductivity gauges.

### **DEAD WEIGHT PISTON GAUGE:-**

The dead weight tester is a primary standard for pressure measurement, and it offers a good calibration facility over a wide pressure range ( $700 \text{ N/}^2$  to  $70 \text{ MN/}^2$  gauge in steps as small as 0.01% of range with a calibration uncertainty of 0.01-0.05% of the reading).



*Dead weight piston gauge*

A typical gauge is schematically shown in Fig. It consists of an accurately machined, bored and finished piston which is inserted into a close fitting cylinder; both of known cross- section areas. A platform is attached to the top of the piston and it serves to hold standard weights of known accuracy. The chamber and the cylinder are filled with a clean oil; the oil being supplied from an oil reservoir provide with a check valve at its bottom. The oil withdrawn from the reservoir when the pump plunger executes an outward stroke and forced into the space below the piston during inward motion of the pump plunger. For calibrating a gauge, an appropriate amount of weight is placed on the platform and the fluid pressure is applied until enough upward force is developed to lift the piston-weight combination. When this occurs, the piston-weight combination begins to float freely within the cylinder.

Under the equilibrium condition the pressure force is balanced against the gravity force on the mass 'm' of the calibrated masses, plus the piston and flat form and a frictional force. If 'A' is the equivalent area of the piston cylinder combination then:

$$PA = mg + \text{frictional drag.}$$

$$P = (mg + \text{frictional drag})/A$$

The effective or equivalent area depends on such factors as piston cylinder clearance, pressure level, temperature, and is normally taken as the mean of the cylinder and piston areas.

### **Manometers:-**

Manometers measure pressure by balancing a column of liquid against the pressure to be measured. Height of column so balanced is noted and then converted to the desired units. Manometers may be vertical, inclined, open, differential or compound. Choice of any type depends on its sensitivity of measurement, ease of operation and the magnitude of pressure being measured. Manometers can be used to measure gauge, differential, atmospheric, and absolute pressure.

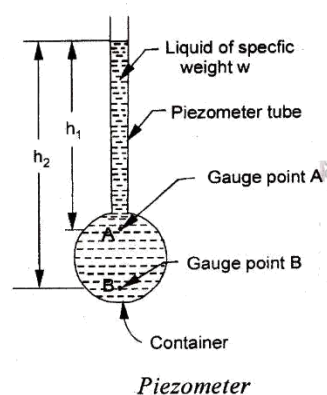
i. Piezo meter

7. U- tube manometer

8. Single column manometer

#### **i. Piezo meter:**

It is a vertical transparent glass tube, the upper end of which is open to atmosphere and the lower end is in communication with the gauge point ; a point in the fluid container at which pressure is to be measured. Rise of fluid in the tube above a certain gauge point is a measure of the pressure at that point.



Fluid pressure at gauge point A = atmospheric pressure  $p_u$  at the free surface + pressure due to a liquid column of height  $h_1$

$$p_1 = p_u + h_1 w$$

Where,  $w$  is the specific weight of the liquid.

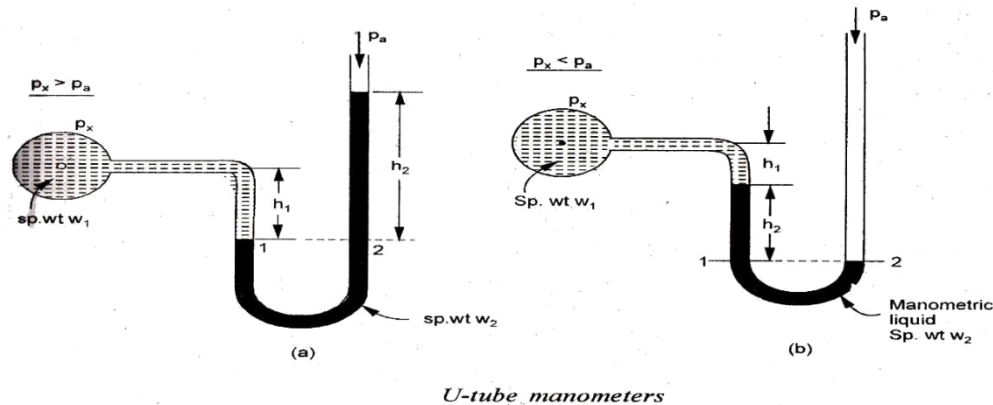
Similarly for the gauge point B

$$p_2 = p_u + h_2 w$$

#### **ii. U- tube manometer:**

This simplest and useful pressure measuring consists of a transparent tube bent in the form of letter U and filled with a particular liquid whose density is known. The choice of a particular manometric liquid

upon the pressure range and nature of the fluid whose pressure is sought. For high mercury (specific gravity 13.6) is the manometric/balancing liquid. For low pressure liquids like carbon tetrachloride (specific gravity 1.59) or acetylene tetrabromide (specific gravity 2.59) are employed. Quite often, some colours are added to the balancing so as to get clear readings.



U-tube manometers

#### (a) Measurement of pressure greater than atmospheric pressure:

Due to greater pressure in the container, the manometric liquid is forced downward the left limb of the U-tube and there is a corresponding rise of manometric liquid in the right limb.

Let,  $h_1$  = height of the light liquid above the datum line

$h_2$  = height of the heavy liquid above the datum line

For the right limb the gauge pressure at point 2 is

$p_2$  = atmospheric pressure, i.e., zero gauge pressure at the free surface + pressure due to head  $h_2$  of manometric liquid of specific weight  $w_2$

$$p_2 = 0 + w_2 h_2$$

For the left limb, the gauge pressure at point 1 is

$p_1$  = gauge pressure + pressure due to height  $h_1$  of the liquid of specific weight  $w_1$

$$p_1 = p + w_1 h_1$$

Points 1 and 2 are at the same horizontal plane;  $p_1 = p_2$  and therefore,

$$p + w_1 h_1 = w_2 h_2$$

Gauge pressure in the container,  $p = w_2 h_2 - w_1 h_1$

### (b) Measurement of pressure less than atmospheric pressure:

Due to negative pressure in the container, the manometric liquid is sucked upwards in the left limb of the U-tube and there is a corresponding fall of manometric liquid in the right limb.

Pressure in the two legs at the same level 1 and 2 are equal;  $p_1 = p_2$  and therefore, Gauge pressure in the container,  $= -(p_1 h_1 = p_2 h_2)$

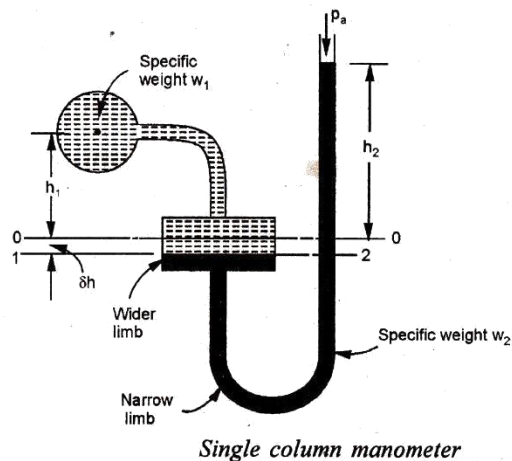
### iii. Single column manometer:

Single column manometer is modified form of manometer in which a reservoir having a large cross sectional area as compared to the area of the tube, is connected to one of the limbs (say left limb) of the reservoir. The other limb may be vertical or inclined. There are two types of single column manometers.

☐ Vertical single column manometer

☐ Inclined single column manometer

#### 1. Vertical single column manometer:



To start with, let both limbs of the manometer be exposed to atmospheric pressure. Then the liquid level in the wider limb (also called reservoir well basin) and narrow limbs will correspond to position 0-0.

$h_1$  = height of center of pipe above 0-0

$h_2$  = rise of heavy liquid in right limb

For the left limb, gauge pressure at point 1 is:  $p_1 = p_a + w_1 h_1 + w_1 h$

For the right limb, the gauge pressure at point 2 is:  $p_2 = 0 + w_2 h_2 + w_2 h$

Points 1 and 2 are at the same horizontal plane:  $p_1 = p_2$  and therefore

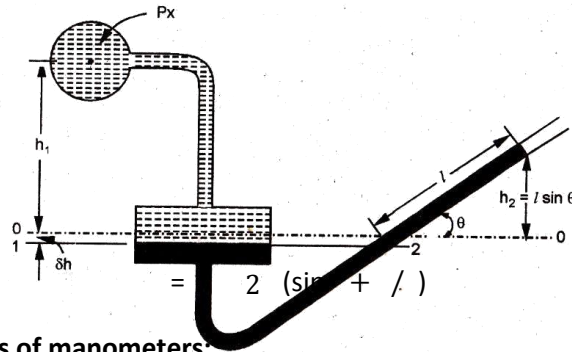
Gauge pressure in the container is:  $= (2 h_2 - 1 h_1) + h (2 - 1)$

## 2. Inclined single column manometer:

This manometer is more sensitive. Due to inclination the distance moved by heavy liquid in the right limb will be more.

Let,  $l$  = length of heavy liquid moved in right limb from 0-0

$\theta$  = Inclination of right limb with horizontal.



### Advantages and limitations of manometers:

- 10) Relatively inexpensive and easy to fabricate
- 11) good accuracy and sensitivity
- 12) requires little maintenance; are not affected by vibrations
- 13) particularly suitable to low pressures and low differential pressures
- 14) sensitivity can be altered easily by affecting a change in the quantity of manometric liquid in the manometer
- 15) generally large and bulky, fragile and gets easily broken
- 16) not suitable for recording
- 17) measured medium has to be compatible with the manometric fluid used
- 18) readings are affected by changes in gravity, temperature and altitude
- 19) surface tension of manometric fluid creates a capillary effect and possible hysteresis
- 20) meniscus height, has to be determined by accurate means to ensure improved accuracy.

### **Mechanical Gauges: - Elastic Pressure Transducer:-**

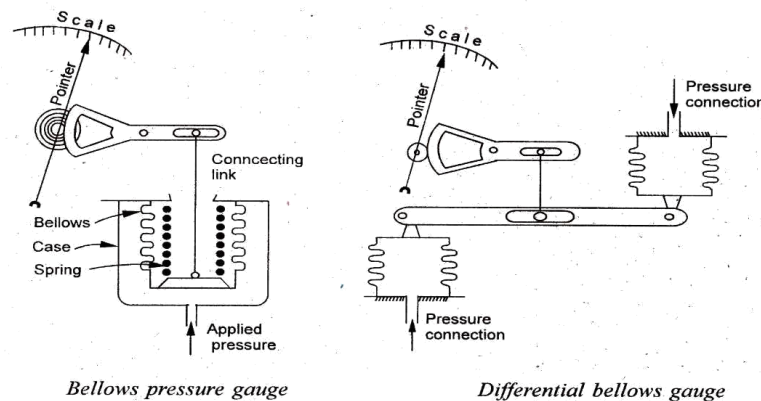
For measuring pressures in excess of two atmosphere elastic mechanical type transducers are used. The actions of these gauges are based on the deflection of the hollow tube, diaphragm and bellows caused by the applied pressure difference. The resulting deflection made directly accurate a pointer. Scale read out through suitable linkages and gears are the motion may be transmitted through and electrical signal. Bellows and diaphragm gauges are generally suitable up to 28 to 56 bars. Where as bourdon tubes are very high pressure gauges.

#### **Bellow gauges:**

The bellows is a longitudinally expansible and collapsible member consisting of several convolutions or folds. The general acceptable methods of fabrication are:

❑ turning from a solid stock of metal, (ii) soldering or welding stamped annular rings, (iii) rolling a tubing, and (iv) hydraulically forming a drawn tube. Material selection is generally based on considerations like strength or the pressure range, hysteresis and fatigue.

In the differential pressure arrangement (Fig) two bellows are connected to the ends of an equal arm lever. If equal pressures are applied to the two bellows, they would extend by the same amount. The connecting lever would then rotate but no movement would result in the movement sector. Under a differential pressure, the deflections of the bellow would be unequal and the differential displacement of the connecting levers would be indicated by the movement of the pointer on a scale.



#### **Advantages:**

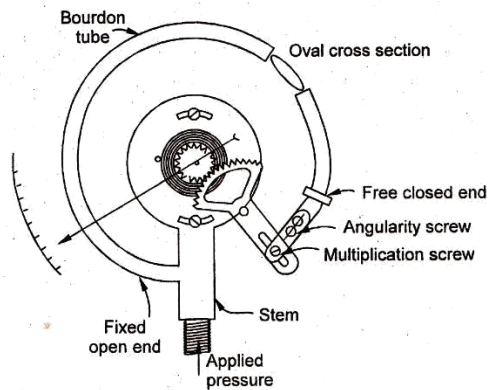
- f) Simple in construction.
- g) Good for low to moderate pressures.
- h) Available for gauge, differential and absolute pressure measurements.
- i) Moderate cost.



Limitations:

- viii. Zero shift problems.
- ix. Needs spring for accurate characterization.
- x. Requires compensation for temperature ambient changes.

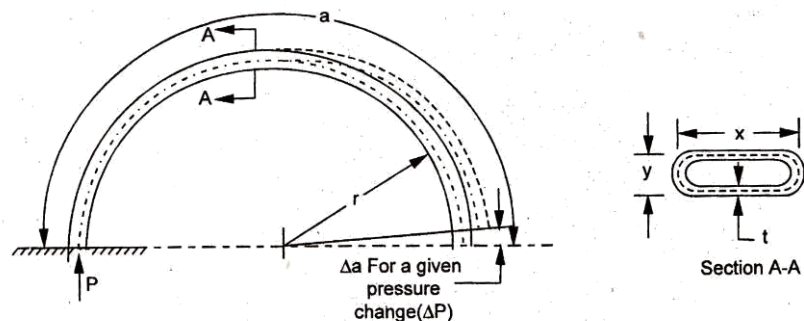
### **BOURDON GAUGE:-**



*Bourdon tube pressure transducer*

The pressure responsive element of a bourdon gauge consists essentially of metal tube (called bourdon tube or spring), oval in cross section and bent to form a circular segment of, approximately 200 to 300 degrees. The tube is fixed but open at one end and it is through this fixed end that the pressure to be measured is applied. The other end is closed but free to allow displacement under deforming action of the pressure difference across the tube walls. When a pressure (greater than atmosphere) is applied to the inside of the tube, its cross-section tends to become circular. This makes the tube straighten itself out with a consequent increase in its radius of curvature, i. e., the free end would collapse and curve.

**Type travel:**



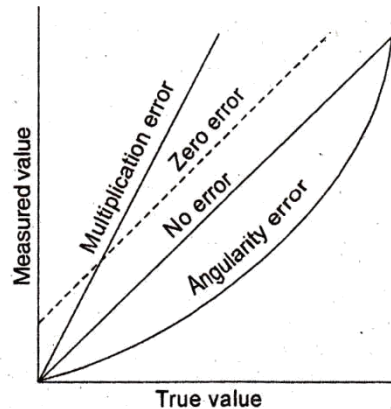
*Geometry of a C-type bourdon tube*

The motion of the free end commonly called tip travel is a function of tube length wall thickness, cross sectional geometry and modulus of the tube material. For a bourdon tube a deflection  $\Delta a$  of the elemental tip can be expressed as

$$\Delta a = \frac{P L^3}{4 E I} \left( \frac{1}{2} - \frac{1}{2} \cos \frac{a}{2} \right)$$

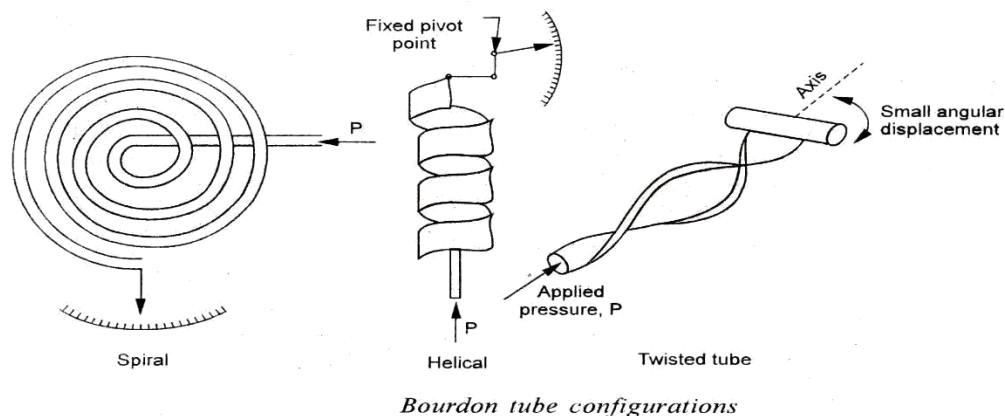
Where 'a' is the total angle subtended by the tube before pressurization, P is the applied pressure difference and 'E' is the modulus of elasticity of the tube material.

**Errors and their rectification: in general 3 types of error are found in bourdon gauges:**



- ❑ Zero error or constant error which remains constant over the entire pressure range.
- ❑ Multiplication error where in the gauge may tend to give progressively a higher or low reading.
- ❑ Angularity error: quite often it is seen that a one-to-one correspondence does not occur.

**Bourdon tube shapes and configurations:**



The C-type bourdon tube has a small tip travel and this necessitates amplification by a lever, quadrant, pinion and pointer arrangement. Increased sensitivity can be obtained by using a very long length of tubing in the form of a helix, and a flat spiral as indicated in Fig.

Materials:

- 10) Pressure 100 to 700 KN/m<sup>2</sup> (tubes are made of phosphor bronze)
- 11) For high pressure P=7000 to 63000 KN/m<sup>2</sup> (tubes are made of alloy steel or k-monel)

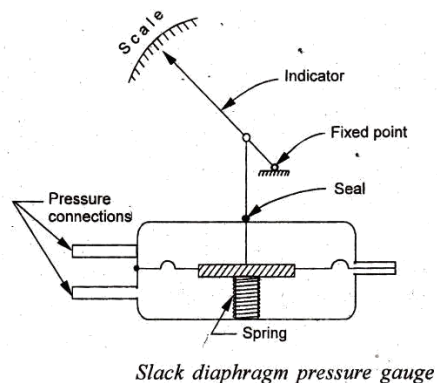
Advantages:

- 6) Low cost and simple in construction.
- 7) Capability to measure gauge absolute and differential pressure.
- 8) Availability in several ranges.

Limitations:

- (vi) So response.
- (vii) Susceptibility to sharp and vibration.
- (viii) Mutually required geared movement for application.

### DIAPHRAGM GAUGES:-



In its elementary form, a diaphragm is a thin plate of circular shape clamped firmly around its edges. The diaphragm gets deflected in accordance with the pressure differential across the side; deflection being towards the low pressure side. The pressure to be measured is applied to diaphragm causing it to deflect the deflection being proportional to applied pressure. The movement of diaphragm depends on its thickness and diameter. The pressure deflection relation for a flat diaphragm with adjustable clamped is given by

$$P = \frac{16Et^4}{3r^4(1-\mu^2)} \left[ \frac{y}{t} + 0.488 \left( \frac{y}{t} \right)^3 \right]$$

Where, P=pressure difference across the diaphragm, E=modulus of elasticity, t= diaphragm thickness

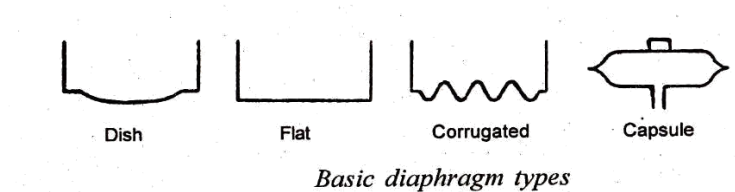
M= Poisson's ratio, R=diaphragm radius, Y=deflection at center of diaphragm.

There are two basic types of diaphragm element design:

C) Metallic diaphragm which depends upon its own resilience for its operation.

D) Non-metallic or slack diaphragm which employs a soft, flexible material with no elastic characteristic.

**Diaphragm types:** The diaphragms can be in the form of flat, corrugated or dished plates; the choice depending on the strength and amount of deflection desired. Most common types of diaphragms are shown in Fig.



**Diaphragm material, pressure ranges and applications:** Metallic diaphragms are generally fabricated from a full hard, cold-rolled nickel, chromium or iron alloy which can have an elastic limit up to 560 MN/ml. Typical pressure ranges are 0 - 50 mm water gauge, 0-2800 kN/m<sup>2</sup> pressure and 0 - 50 mm water gauge vacuum.

Typical applications are low pressure absolute pressure gauges, draft gauges, liquid level gauges and many types of recorders and controllers operating in the low range of direct or differential pressures.

Non-metallic slack diaphragms are made a variety of materials such as gold beaters, silk, animal membranes, impregnated silk clothes and synthetic materials like Teflon, neoprene, polythene ...Etc.

**Advantages:**

- v) Relatively small size and moderate cost.
- vi) Capability to withstand high over pressures and maintain good linearity over a wide range.
- vii) Availability of gauge for absolute and differential pressure measurement.
- viii) Minimum of hysteresis and no permanent zero shift.

**Limitations:-**

- 4) Needs protection from shocks and vibrations.
- 5) Cannot be used to measure high pressure.
- 6) Difficult to repair.

#### **LOW PRESSURE GAUGES: -**

Below 1 mm of mercury (Hg) is known as low pressure gauges. Pressure ranges:

Low vacuum = 760 torr to 25 torr,                      Medium vacuum = 25 torr to 10<sup>-3</sup> torr,  
High vacuum = 10<sup>-3</sup> torr to 10<sup>-6</sup> torr, Very high vacuum = 10<sup>-6</sup> torr to 10<sup>-9</sup> torr, Ultra high vacuum = 10<sup>-9</sup> torr and beyond.

Low pressure gauges are grouped into two types. They are

5. Direct measurement: wherein displacement deflection caused by the pressure is measured and is correlated to the applied pressure. This principle is incorporated in bellows, diaphragm, bourdon tube, manometer.

6. Indirect type measurements: wherein the low pressure is detected through measurement of a pressure controlled property such as volume, thermal conductivity etc. the inferential gauges include Thermal conductivity gauges, Ionization gauge, McLeod gauge.

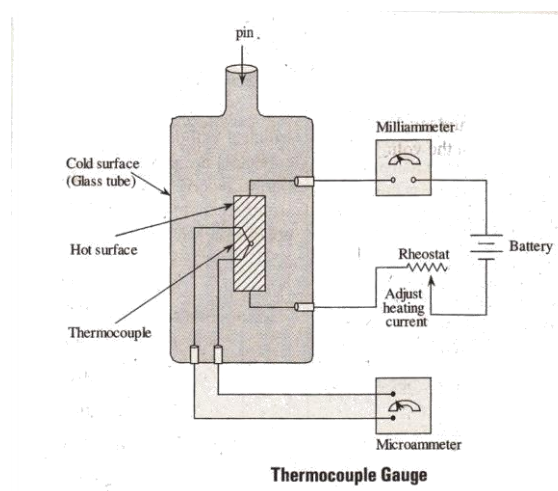
### **THERMAL CONDUCTIVITY GAUGES: -**

These gauges measure pressure through a change in the thermal conductivity of the gas. Their operation is based on the thermodynamic principle that “at low pressures there is a relationship between the pressure and thermal conductivity i.e., the heat conductivity decreases with decrease in pressure”. There are two types of thermal gauges.

d) Thermocouple gauge.

e) Pirani gauge.

#### **1. Thermocouple gauge:**

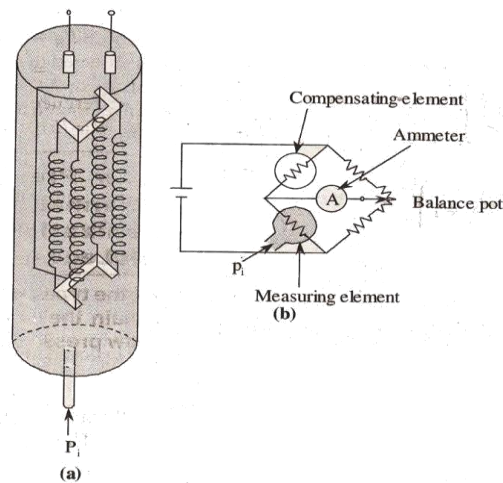


The schematic diagram of a thermocouple type conductivity gauge is shown in figure (1). The pressure to be measured is admitted to a chamber. A constant current is passed through the thin metal strip in the chamber.

Due to this current, the metal strip gets heated and acts as a hot surface. The temperature of this hot surface is sensed by a thermocouple which is attached to the metal strip. The glass tube acts as the cold surface, whose temperature is nearly equal to room temperature. The conductivity of the metal strip changes due to the applied pressure. This change in conductivity causes a change in the temperature, which is sensed by the thermocouple. The thermocouple produces a current corresponding to the thermocouple output, which is then indicated by a mm. This indicated current becomes a measure of the applied pressure when calibrated.

## 2. Pirani gauge:

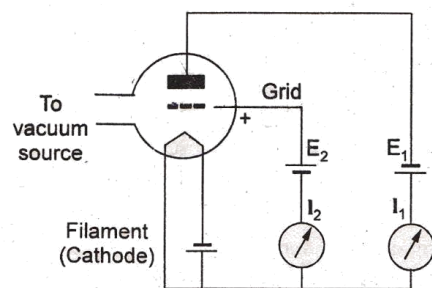
The construction of a pirani gauge is shown in fig.



Pirani Gauge

It consists of two identical tubes, platinum/tungsten Wire and a compensating element. A constant current is passed through the platinum wire which is mounted along the axis of the glass tube. The wire gets heated due to this current and its resistance is measured using a resistance bridge. The gas whose pressure to be measured is admitted to the glass tube. The conductivity of the Wire changes due to this applied pressure. This change in conductivity causes a change in temperature of the wire which in turn causes, a change in the resistance of the wire. This change in resistance is measured using the resistance bridge. The other tube present in the gauge is evaluated to a very low pressure and it acts as a compensating element to minimize the variations caused by ambient temperature changes.

## IONIZATION GAUGE:-



Hot filament ionisation gauge

The hot filament ionization gauge consists of a heated filament (cathode) to furnish electrons, a grid, and an anode plate. These elements are housed in an envelop which communicates with the vacuum system under test. The grid is maintained at a positive potential of 100-350 V while the anode plate is maintained at negative potential of about 3-50 V with respect to cathode. The cathode is thus a positive ion collector and the anode plate is an electron collector.

The rate of ion production is proportional to the number of electrons available to ionize the gas and the amount of gas present. Thus the ratio of +ve ions, i. e., the anode current  $I_1$  to -ve ions and electrons, i.e., grid current  $I_2$  is a measure of the gas pressure  $P$ . The following approximate relation holds:

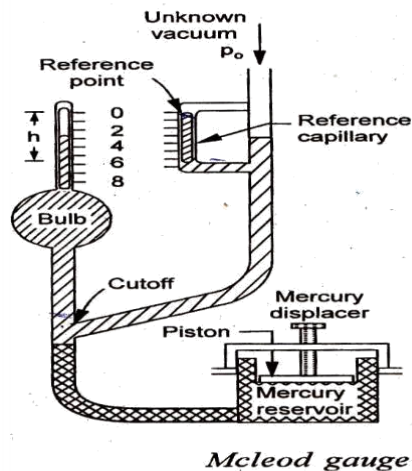
$$I_1/I_2 = S P$$

Where the proportionality constant  $S$  is called the sensitivity of the gauge. Sensitivity is a function of the tube geometry, nature of the gas, and the operating voltages. Its value is determined by calibration of the particular gauge.

Advantages:-

- l) Wide pressure range  $10^{-3}$  torr to  $10^{-11}$  torr.
- m) Constant sensitivity.
- n) Possibility of process control and remote indication.
- o) Fast response to pressure changes.
- p) High cost and complex electrical circuit.
- q) Calibration varies with gases.
- r) Filament burns out if exposed to air by hot.
- s) Decomposition of some gases by the hot filament.
- t) Contamination of gas due to heat.

#### MCLEOD GAUGE:-



The unit comprises the system of glass tubes in which a known volume of gas at unknown pressure is trapped and then isothermally compressed by a rising mercury column. Its operation involves the following steps:

(x) Plunger is withdrawn and the mercury level is lowered to the cut off position, thereby admitting gas at unknown pressure ' $P_0$ ' into the system. Let ' $V_0$ ' be the volume of the gas admitted into the measuring capillary, the bulb and into the tube down to the cutoff points.

(i) The plunger is pushed in and the mercury level goes up. The plunger motion is continued until the mercury level in the reference capillary reaches the zero mark. Let height 'h' be the measure of the compressed gas volume sealed into the measuring capillary. This height also represents rise in gas pressure in terms of height of mercury column.

If 'a' denotes the area of the measuring capillary then the final volume  $V_f = a \cdot h$  and the final monomeric pressure  $P_f = P_0 + h$ . The unknown pressure is then calculated using Boyle's law as follows:

$$PV = \text{Constant}$$

$$P_0 V_0 = P_f V_f$$

$$P_0 V_0 = (P_0 + h)(ah)$$

$$P_0 (V_0 - ah) = ah^2$$

$$P_0 = \frac{(P_0 + h)ah}{V_0} \Rightarrow P_0 \left( \frac{ah}{V_0} \right) + \frac{h(ah)}{V_0}$$

$$P_0 \left( 1 - \frac{ah}{V_0} \right) = \frac{ah^2}{V_0}$$

$$P_0 = \frac{ah^2}{V_0} \times \frac{V_0}{(V_0 - ah)}$$

$$P_0 = \frac{ah^2}{V_0 - ah}$$

If  $ah \ll V_0$ , as is usually the case, then

$$P_0 = \frac{ah^2}{V_0}$$

This is one type of manometer. This is used for calibration of Pirani and thermocouple gauges.



# UNIT -III

## Measurement of Liquid and Flow



### Measurement of Liquid Level:-

Liquid level refers to the position or height of a liquid surface above a datum line.

Level measurements are made to a certain quantity of the liquid held within a container.

Level offers both the pressure and rate of flow in and out of the container and as such its measurement and control is an important function in a variety of processes. The task of liquid level measurement may be accomplished by direct methods and indirect methods.

(1) Direct methods

(2) Indirect methods

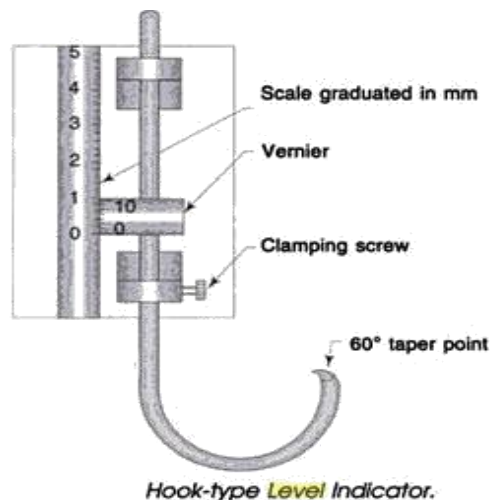
#### (1) Direct methods:-

This is the simplest method of measuring liquid level. In this method, the level of liquid is measured directly by means of the following level indicators:

7. Hook-type Level Indicator
8. Sight Glass
9. Float-type
10. Float and shaft liquid level gauge.

#### (i) Hook-type Level Indicator:

When the level of liquid in an open tank is measured directly on a scale (the scale may be in the liquid or outside it), it is sometimes difficult to read the level accurately because of parallax error. In this case a hook type of level indicator is used.



### Construction:

Hook-type level indicator consists of a wire of corrosion resisting alloy (such as stainless steel) about  $\frac{1}{4}$  in (0.063 mm) diameter. Bent into U-Shape with one arm longer than the other as shown in Fig. The shorter arm is pointed with a  $60^\circ$  taper. While the longer one is attached to a slider having a Vernier scale. Which moves over the main scale and indicates the level.

### Working:

In hook-type level indicator, the hook is pushed below the surface of liquid whose level is to be measured and gradually raised until the point is just about to break through the surface. It is then clamped, and the level is read on the scale. This principle is further utilized in the measuring point manometer in which the measuring point consists of a steel point fixed with the point upwards underneath the water surface.

### (ii) Sight Glass:

A sight glass (also called a gauge glass) is another method of liquid level measurement. It is used for the continuous indication of liquid level within, tank or vessel.



### Construction and working:

A sight glass instrument consists of a graduated tube of toughened glass which is connected to the interior of the tank at the bottom in which the water level is required. Figure shows a simple sight glass for an open tank in which the liquid level in the sight glass matches the level of liquid in the tank. As the level of liquid in the tank rises and falls, the level in the sight glass also rises and falls accordingly. Thus, by measuring the level in the sight glass, the level of liquid in the tank is measured. In sight glass, it is not necessary to use the same liquid as in the tank. Any other desired liquid also can be used.

### (iii) Float-type:

Float-Type Level Indicator most operated level indicator is used to measure liquid levels in a tank in which a float rests on the surface of liquid and follows the changing level of liquid. The movement of the float is transmitted to a pointer through a suitable mechanism which indicates the level on a calibrated scale. Various types of floats are used such as hollow metal spheres, cylindrical-shaped floats and disc-shaped floats.

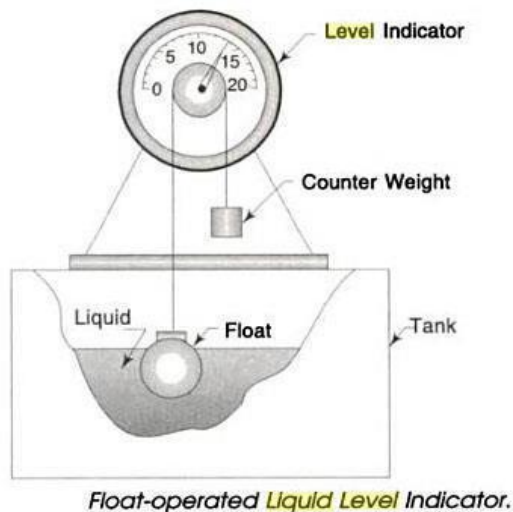
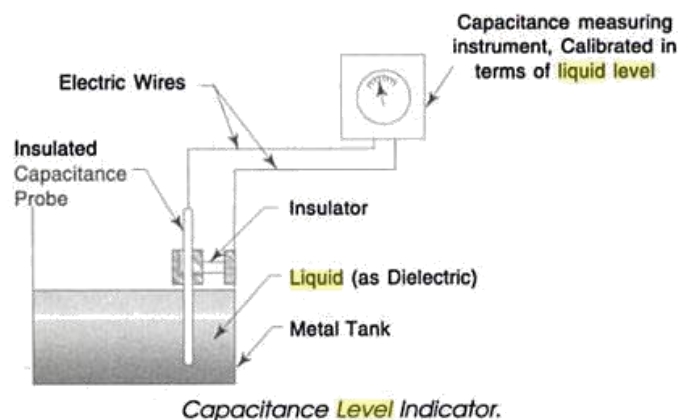


Figure shows the simplest form of float operated mechanism for the continuous liquid level measurement. In this case, the movement of the float is transmitted to the pointer by stainless steel or phosphor-bronze flexible cable wound around a pulley, and the pointer indicates liquid level in the tank. The float is made of corrosion resisting material (such as stainless steel) and rests on liquid level surface between two grids to avoid error due to turbulence, With this type of instrument, liquid level from ½ ft. (152 mm) to 60, ft. (1.52 m) can be easily measured.

## **(2) INDIRECT METHODS:**

Indirect methods liquid level measurements converts the changes in liquid level into some other form such as resistive, capacitive or inductive beyond force, hydrostatic pressure ... Etc. and measures them. Thus the change occurred in these parameters gives the measures of liquid level.

### **(i) CAPACITIVE LIQUID LEVEL SENSOR:**



The principle of operation of capacitance level indicator is based upon the familiar capacitance equation of a parallel plate capacitor given by:

where, C = Capacitance, in farad

K = Dielectric constant

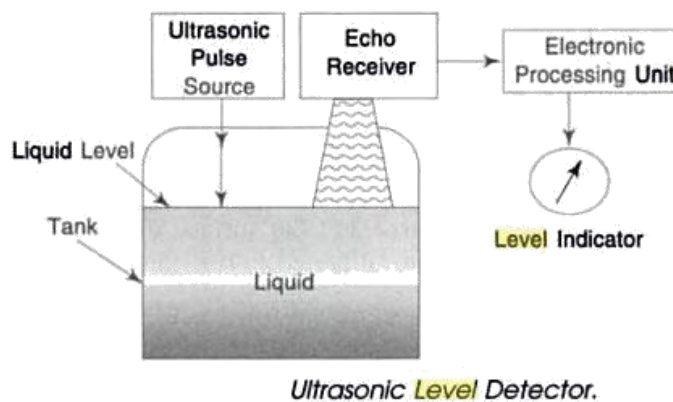
A = area of plate, in  $\text{m}^2$

D = Distance between two plates. in m

Therefore, it is seen from the above relation that if A and D are constant, then the capacitance of a capacitor is directly proportional to the dielectric constant, and this principle is utilized in the capacitance level indicator.

Figure shows a capacitance type Liquid level indicator. It consists of an insulated capacitance probe (which is a metal electrode) firmly fixed near and parallel to the main wall of the tank. If liquid in the tank is non-inductive, the capacitance probe and the tank wall form the plates of a parallel plate capacitor and liquid in between them acts as the dielectric. If liquid is conductive, the capacitance probe and liquid form the plates of the capacitor and the insulation of the probe acts as the dielectric. A capacitance measuring device is connected with the probe and the tank wall, which is calibrated in terms of the level of liquid in the tank.

## (ii) Ultrasonic method:



Ultrasonic liquid level works on the principle of reflection of the sound wave from the surface of the liquid. The schematic arrangement of liquid level measurement by ultrasonic liquid level gauge is illustrated above.

The transmitter 'T' sends the ultrasonic wave towards the free surface of the liquid. The wave gets reflected from the surface. The reflected waves received by the receiver 'R'. The time taken by the transmitted wave to travel to the surface of the liquid and then back to the receiver gives the level of

the liquid. As the level of the liquid reaches the time taken to reach the surface of the liquid and then back to receiver also changes. Thus the change in the level of the liquid are determined accurately.

Advantages:-

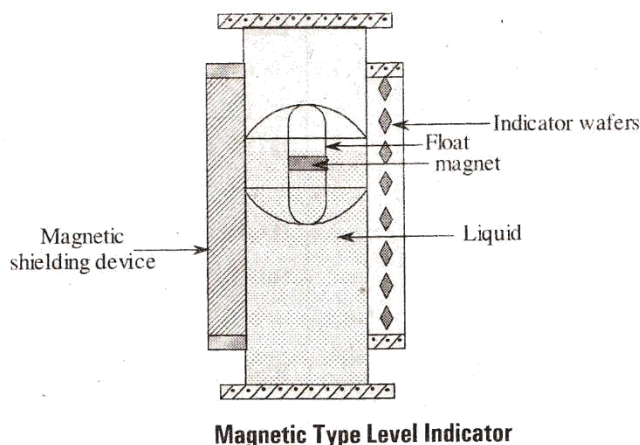
- viii. Operating principle is very simple.
- ix. It can be used for various types of liquids and solid substances.

Disadvantages:-

Very expensive.

Very experienced and skilled operator is required for measurement.

## 9. MAGNETIC TYPE LEVEL INDICATORS:

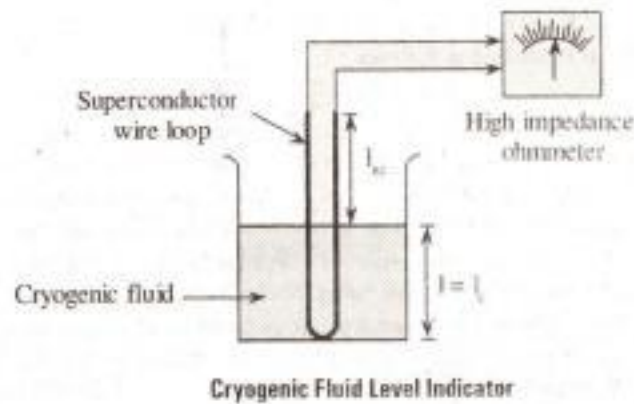


These are used for measuring the toxic and corrosive liquids. It is used to measure the level of liquids which contain corrosive and toxic materials.

It contains a float in which a magnet is arranged and is placed in the chamber, whose liquid level is to be determined. The float moves up and down with the increase and decrease in the level of liquid respectively. A magnetic shielding device and an indicator containing small wafers arranged in series and attached to the sealed chamber. These wafers are coated with luminous paint and rotate 180°. As the level changes the float moves (along with the magnet) up and down. Due to this movement of magnet, wafers rotate and present a black coloured surface for the movement of float in opposite direction.

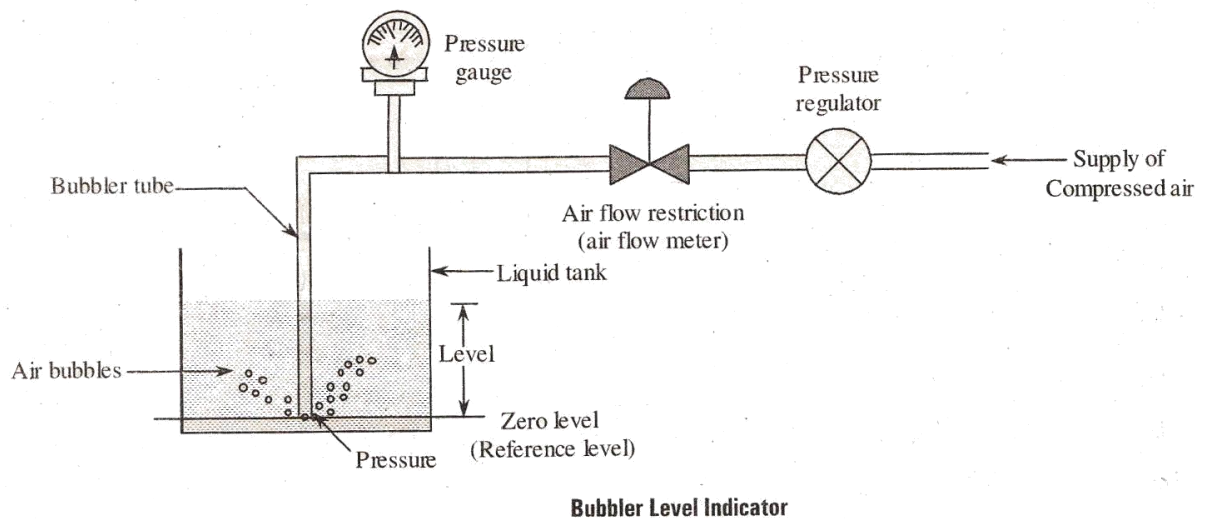
### (iv) Cryogenic fuel level indicator:

A gas which changes its state (gaseous state into liquid state). When cooled to very low temperatures is known as cryogenic fluid. A cryogenic fluid exists in liquid state at very low temperatures, which are usually less than the temperature levels at which a superconductor exhibits zero resistance characteristic.



#### (v) Bubbler level indicator:

The Bubbler type level indicator is also known as purge type of liquid level meter.



In this technique of level measurement, the air pressure in the pneumatic pipeline is adjusted and maintained slightly greater than the hydrostatic pressure at the lower end of the bubbler tube. The bubbler tube is dipped in the tank such that its lower end is at zero level i.e., reference level, and the other end is attached to a pressure regulator and a pressure gauge. Now the supply of air through the bubbler tube is adjusted so that the air pressure is slightly higher than the pressure exerted by the liquid column in the vessel or tank. This is accomplished by adjusting the air pressure regulator until a slow discharge of air takes place i.e., bubbles are seen leaving the lower end of the bubbler tube. (In some cases a small air flow meter is arranged to control an excessive air flow if any). When there is a small flow of air and the fluid has uniform density, the pressure indicated by the pressure gauge is directly

proportional to the height of the level in the tank provided the gauge is calibrated properly in unit of liquid level.



### **FLOW MEASUREMENT:-**

**Introduction:** Measurement of fluid velocity, flow rate and flow quantity with varying degree of accuracy or a fundamental necessity in almost all the flow situations of engineering. Studying ocean or air currents, monitoring gas input into a vacuum chamber, measuring blood movement in a vein. The scientist or engineer is faced with choosing a method to measure flow. For experiment procedures, it may be necessary to measure the rates of flow either into or out of the engines. "Pumps, compressors and turbines". In industrial organizations flow measurement is needed for providing the basis for controlling processes and operations. That is for determining the proportions of materials entering or leaving, a continuous manufacturing process. Flow measurements are also made for the purpose of cost accounting in distribution of water and gas to domestic consumers, and in the gasoline pumping stations.

### **TYPES OF FLOW MEASURING INSTRUMENTS:-**

- 8) Quantity meters.
- 9) Flow meters.
- 10) Quantity meters:-

In this class of instruments actual flow rate is measured. Flow rate measurement devices frequently required accurate. Pressure and temperature measurements in order to calculate the output of the instrument. The overall accuracy of the instrument depends upon the accuracy of pressure and temperature measurements.

Quantity meters are used for the calibration of flow meters:

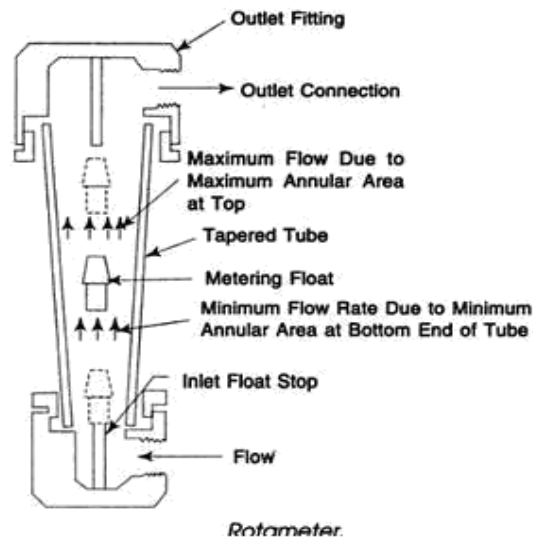
- 21) Quantity meters.
  - 1) Weight or volume tanks.
  - 2) Positive displacement or semi-positive displacement meters.
- 22) Flow meters.
  - Obstruction meters.
    - Orifice
    - Nozzle
    - Venture
    - Variable-area meters.
  - Velocity probes.
    - Static pressure probes.
    - Total pressure probes.
  - Special methods.
    - Turbine type meters.
    - Magnetic flow meters.

Sonic flow meter.  
Hot wire anemometer.  
Mass flow meters.  
Vortex shedding phenomenon.

d. Flow visualization methods.

Shadowgraphy.  
Schlieren photography.  
Interferometry.

**ROTAMETER:-**



The rotameter is the most extensively used form of the variable area flow meter. It consists of a vertical tapered tube with a float which is free to move up or down within the tube as shown in Fig. The tube is made tapered so that there is a linear relationship between the flow rate and position in the float within the tube. The free area between float and inside wall of the tube forms an annular orifice. The tube is mounted vertically with the small end at the bottom. The fluid to be measured enters the tube from the bottom and passes upward around the float and exit at the top. When there is no flow through the rotameter, the float rests at the bottom of the metering tube where the maximum diameter of the float is approximately the same as the bore of the tube. When fluid enters the metering tube, the float moves up, and the flow area of the annular orifice increases. The pressure differential across the annular orifice is proportional to the square of its flow area and to the square of the flow rate. The float is pushed upward until the lifting force produced by the pressure differential across its upper and lower surface is equal to the weight of the float. If the flow rate rises, the pressure differential and hence the lifting force increases temporarily, and the float then rises, widening the annular orifice until the force caused by the pressure differential is again equal to the weight of the float.



Thus, the pressure differential remains constant and the area of the annular orifice (i.e., free area between float and inside wall of the tube) to which the float moves. Changes in proportion to the flow rate. Any decrease in flow rate causes the float to drop to a lower position. Every float position corresponds to one particular flow rate for a fluid of a given density and viscosity. A calibration scale printed on the tube or near it. Provides a direct indication of flow rate. The tube materials of rotameter may be of glass or metal.

**Advantages:-**

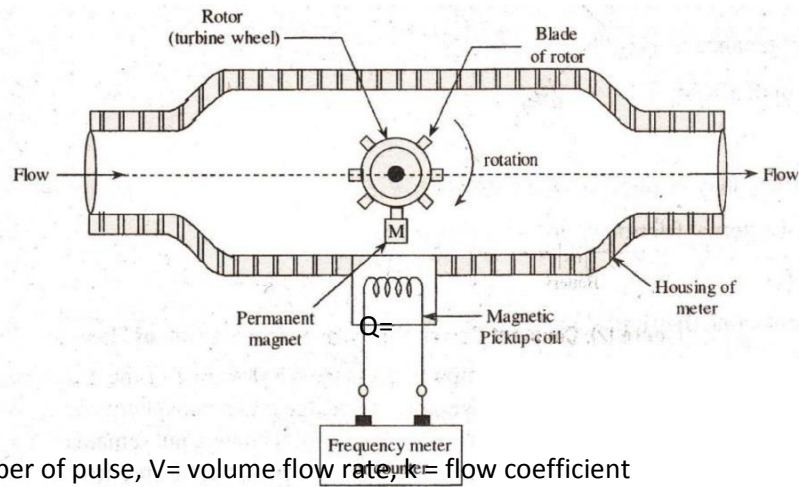
- j) Simplicity of operation.
- k) Ease of reading and installation.
- l) Relatively low cost.
- m) Handles wide variety of corrosive fluids.
- n) Easily equipped with data transmission, indicating and recording devices.

**Disadvantages:-**

- xi. Glass tube subject to breakage.
- xii. Limited to small pipe sizes and capacities.
- xiii. Less accurate compared to venturi and orifice meters.
- xiv. Must be mounted vertically.
- xv. Subject to oscillations.

**TURBINE FLOW METER:-**

Principle: - the permanent magnet attached to the body of rotor is polarized at  $90^\circ$  to the axis of rotation. When the rotor rotates due to the velocity of the fluid (V), the permanent magnet also rotates along with the rotor. Therefore, a rotating magnetic field will be generated which is then cut by the pickup coil. Due to this ac-voltage pulses are generated whose frequency is directly proportional to the flow rate.



Where,  $f$  = total number of pulse,  $V$  = volume flow rate,  $k$  = flow coefficient

### Turbine Flow Meter

By minimizing the bearing friction and other losses that device can be designed to give linear output.

#### Advantages:-

- ☐ Good accuracy and repeatability.
- ☐ Easy to install and maintain.
- ☐ Low pressure drop.
- ☐ Electrical output is available.
- ☐ Good transient response.

#### Disadvantages:-

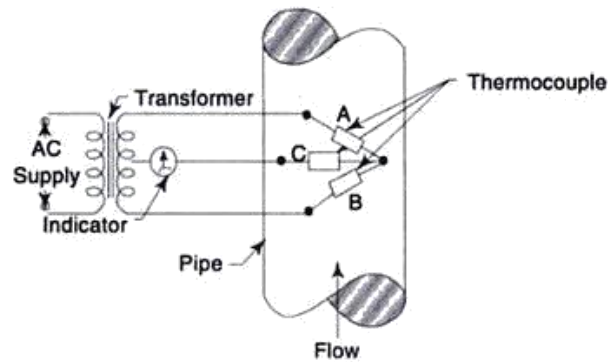
- 12) High cost.
- 13) The bearing of the rotor may subject to corrosion.
- 14) Wear and tear problems.

#### Applications:-

- 9) Used to determine the fluid flow in pipes and tubes.
- 10) Flow of water in rivers.
- 11) Used to determine wind velocity in weather situations or conditions.

## HOT WIRE ANEMOMETER:-

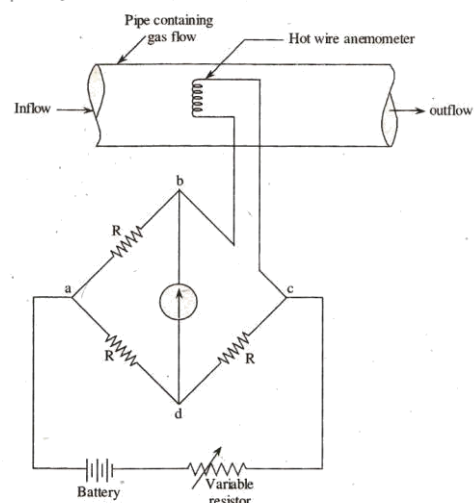
Principle:- When a fluid flows over an electrically heated surface, heat transfer takes place from the surface or wire to the fluid. Hence, the temperature of the heated wire decreases which causes variations in the resistance. The change that occurred in the resistance of the wire is related to the flow rate.



The sensor is a 5 micron diameter platinum tungsten wire welded between the two prongs of the probe and heated electrically as a part of Wheat stone bridge circuit. When the probe is introduced into the fluid flowing, it tends to be cooled by the instantaneous velocity and consequently there is a tendency for the electrical resistance to change. The rate of cooling depends up on the dimensions and physical properties of the wire. Difference of the temperature between the wire and fluid, physical properties of the fluid, string velocity under measurement.

Depending on the associated electronic equipment, the hot wire may be operated in two modes:

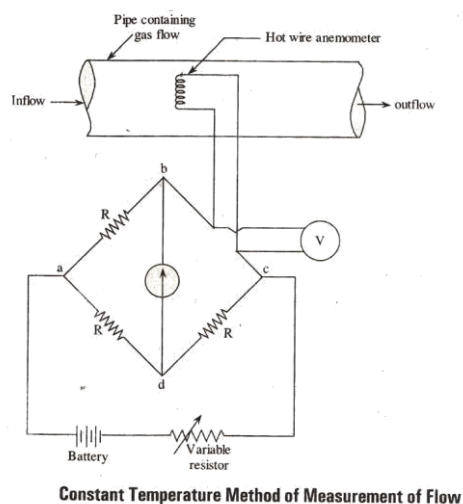
(ix) Constant current mode: -



Here the voltage across the bridge circuit is kept constant. Initially the circuit is adjusted such that the galvanometer reads zero, when the heated wire lies in stationary. Air when the air flows the hot wire

cools, the resistance changes and the galvanometer deflects. The galvanometer deflections are amplified measured in terms of air velocity or liquid velocity or gas velocity.

E) Constant temperature mode: -



Here the resistance of the wire and its temperature is maintained constant in the event of the tendency of the hot wire to cool by the flowing fluid, the external bridge voltage is applied to the wire to maintain a constant temperature. The reading on the voltmeter is recorded and correlated with air velocity.

### **MAGNETIC FLOWMETER: -**

Magnetic flow meter depends up on the faradays law of electromagnetic induction. These meters utilize the principles of faradays law of electromagnetic induction for making a flow measurement. It states that whenever a conductor moves through a magnet field of given field strength; a voltage is induced in the conductor, which is proportional to the relative between the conductor and the magnetic field. In case of magnetic flow meters electrically conductive flowing liquid works as the conductor the induced voltage.

$$e = \quad \times 10^{-8}$$

Where,  $e$ =induced voltage,  $B$ =magnetic flux density in gauss,  $L$ =length of the conductor in cm,  $V$ =velocity of the conductor in m/sec.

The equation of continuity, to convert a velocity measurement to volumetric flow rate is given by

$$Q = AV$$

Where,  $Q$ =volumetric flow rate,  $A$ =cross sectional area of flow meter,  $V$ =fluid velocity.

### Construction and Working:

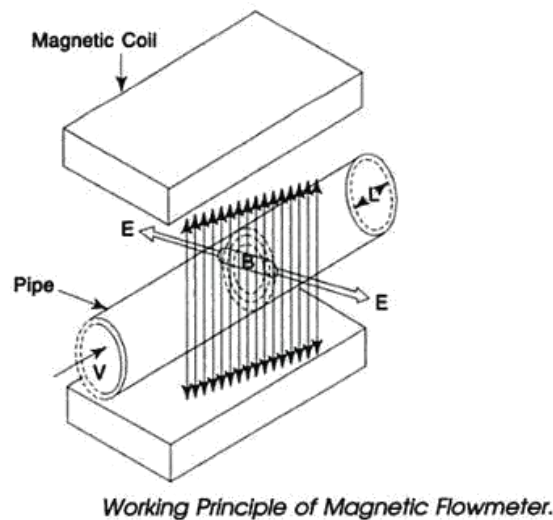


Fig illustrates the basic operating principle of a magnetic flowmeter in which the flowing liquid acts as the conductor. The length  $L$  of which is the distance between the electrodes and equals the pipe diameter. As the liquid passes through the pipe section, it also passes through the magnetic field set up by the magnet coils, thus inducing the voltage in the liquid which is detected by the pair of electrodes mounted in the pipe wall. The amplitude of the induced voltage is proportional to the velocity of the flowing liquid. The magnetic coils may energized either by AC or DC voltage, but the recent development is the pulsed DC-type in which the magnetic coils are periodically energized.

#### Advantages:-

- ix) It can handle greasy materials.
- x) It can handle corrosive fluids.
- xi) Accuracy is good.
- xii) It has very low pressure drop.

#### Disadvantages:-

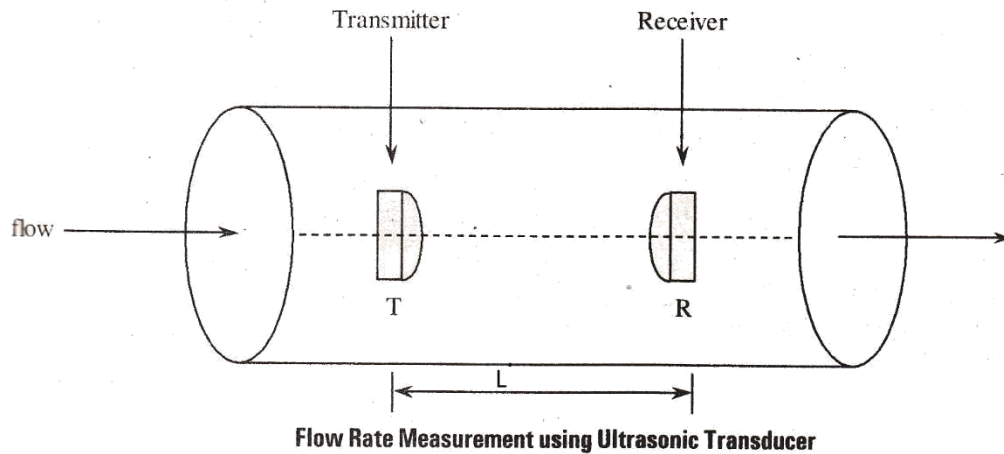
- 7) Cost is more.
- 8) Heavy and larger in sizes.
- 9) Explosion proof when installed in hazardous electrical areas.
- 10) It must be full at all times.

#### Applications:-

- 7. Corrosive acids.
- 8. Cement slurries.
- 9. Paper pulp.
- 10. Detergents.

f) Bear ... Etc.

### ULTRASONIC FLOW METER:-



The velocity of propagation of ultrasonic sound waves in a fluid is changed when the velocity of the flow of fluid changes. The arrangement of flow rate measurement using ultrasonic transducer contains two piezo-electric crystals placed in the fluid whose flow rate is to be measured of these two crystals one acts as a transmitting transducer and the other acts as a receiving transducer. The transmitter and receiver are separated by some distance say "L". Generally the transmitting transducer is placed in the upstream and it transmits ultrasonic pulses. These ultrasonic pulses are then received by the receiving transducer placed at the downstream flow. Let the time taken by the ultrasonic pulsed to travel from the transmitter and received at the receiver is "delta". If the direction of propagation of the signal is same as the direction of flow then the transit time can be given by:

$$\Delta_1 = \frac{L}{V_s + V}$$

Where L=distance between the transmitter and receiver,  $V_s$  =velocity of sound in the fluid,  $V$ =velocity of flow in the pipe.

If the direction of the signal is opposite with the direction of the flow then the transit time is given by:

$$\Delta_2 = \frac{L}{V_s - V}$$

$$\Delta = \Delta_2 - \Delta_1$$

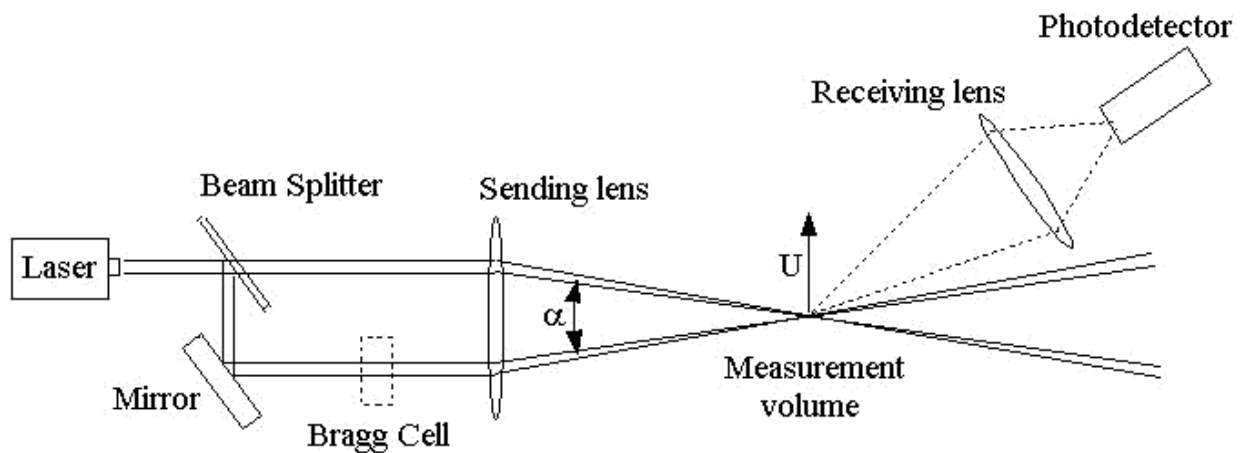
Compared to the velocity of the sound the velocity of the flowing fluid is very very less. So,

$$\Delta = \frac{2}{\dots}$$

Therefore the change in time is directly proportional to the velocity of fluid flow

$$\therefore \Delta \propto$$

### **LASER DOPPLER ANEMOMETER (LDA):-**



The optical flow visualization methods offer the advantage that they do not disturb the flow during the measurement process. The LDA is a device that offers the non-disturbance advantages of optical methods while affording a very precise quantitative measurement of flow velocity. This instrument is the most recent development in the area of flow measurement, especially measurement of high frequency turbulence fluctuation. The operating principle of this instrument involves the focusing of laser beams at a point, where the velocity is to be measured and then sensing with a photo detector. The light scattered by then particles carried along with the fluid as it passes though the laser focal point. The velocity of the particles which is assumed to be equal to the fluid velocity causes a Doppler shift of the frequency of the scattered light and produces a photo detector signal related to the velocity.

$$f = \frac{2 \sin(\frac{\alpha}{2})}{\lambda}$$

= wave length of the laser beam in the flow.



## **MEASUREMENT OF SPEED, ACCLERATION AND VIBRATION**

### **Introduction:**

Speed is a rate variable defined as the time-rate of motion. Common forms and units of speed measurement include: linear speed expressed in meters per second (m/s), and the angular speed of a rotating machine usually expressed in radians per second (rad/s) or revolutions per minute (rpm). Measurement of rotational speed has acquired prominence compared to the measurement of linear speed.

Angular measurements are made with a device called tachometer. The dictionary definitions of a tachometer are:

11. “an instrument used to measure angular velocity as of shaft, either by registering the number of rotations during the period of contact, or by indicating directly the number of rotations per minutes”
12. “an instrument which either continuously indicates the value of rotary speed, or continuously displays a reading of average speed over rapidly operated short intervals of time”

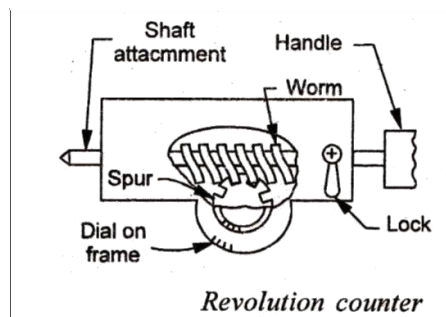
Tachometers may be broadly classified into two categories:

- ξ. Mechanical tachometers and
- ξι. Electrical tachometers.

### **Mechanical tachometers:**

These tachometers employ only mechanical parts and mechanical movements for the measurement of speed.

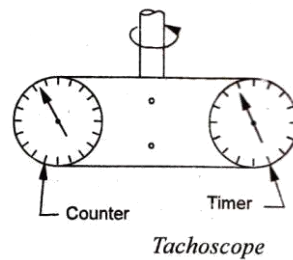
#### **1. Revolution counter and timer:**



The revolution counter, sometimes called a speed counter, consists of a worm gear which is also the shaft attachment and is driven by the speed source. The worm drives the spur gear which in turn actuates the pointer on a calibrated dial. The pointer indicates the number of revolutions turned by the input shaft in a certain length of time. The unit requires a separate timer to measure the time interval. The revolution counter, thus, gives an average rotational speed rather than an instantaneous rotational speed. Such speed counters are limited to low speed engines which permit reading the counter at definite time intervals. A properly designed and manufactured revolution counter would give a satisfactory speed measure upto 2000-3000 rpm.

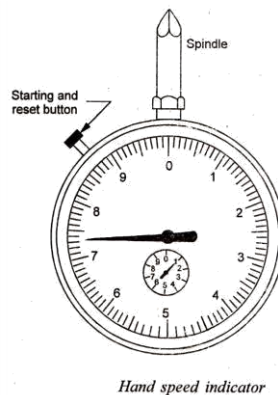


## **2. Tachoscope:**



The difficulty of starting a counter and a watch at exactly the same time led to the development of tachoscope, which consists of a revolution counter incorporating a built-in timing device. The two components are integrally mounted, and start simultaneously when the contact point is pressed against the rotating shaft. The instrument runs until the contact point is disengaged from the shaft. The rotational speed is computed from the readings of the counter and timer. Tachoscopes have been used to measure speeds upto 5000 rpm.

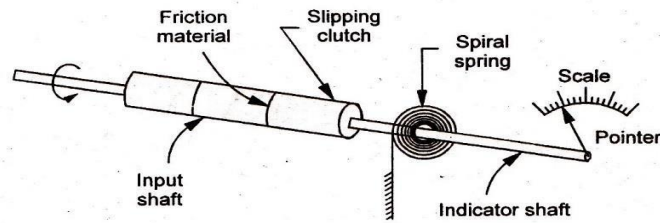
## **3. Hand speed indicator:**



The indicator has an integral stop watch and counter with automatic disconnect. The spindle operates when brought in contact with the shaft, but the counter does not function until the start and wind button is pressed to start the watch and engage the automatic clutch. Depressing of the starting button also serves to wind the starting watch. After a fixed time-interval (usually 3 or 6 seconds), the revolution counter automatically gets disengaged. The instrument indicates the average speed over the short interval, and the dial is designed to indicate the rotational speed directly in rpm. These speed measuring units have an accuracy of about 1% of the full scale and have been used for speeds within the range 20,000 to 30,000 rpm.

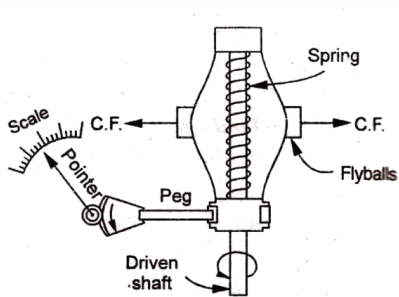
## **4. Slipping clutch tachometer:**

The rotating shaft drives an indicating shaft through a slipping clutch. A pointer attached to the indicator shaft moves over a calibrated scale against the torque of a spring. The pointer position gives a measure of the shaft speed.



*Slipping clutch tachometer*

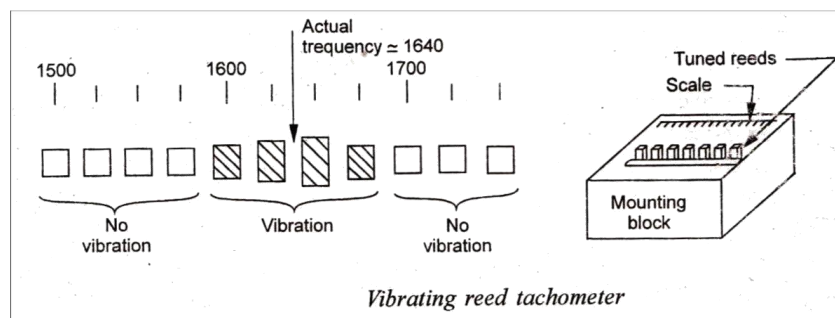
### 5. Centrifugal force tachometers:



*Centrifugal tachometer*

The device operates on the principle that centrifugal force is proportional to the speed of rotation. Two flyballs (small weights) are arranged about a central spindle. Centrifugal force developed by these rotating balls works to compress the spring as a function of rotational speed. A grooved collar or sleeve attached to the free end of the spring then slides on the spindle and its position can be calibrated in terms of the shaft speed. Through a series of linkages, the motion of the sleeve is usually amplified and communicated to the pointer of the instrument to indicate speed. Certain attachments can be mounted onto the spindle to use these tachometers for the measurement of linear speed.

### 6. Vibrating reed tachometer:



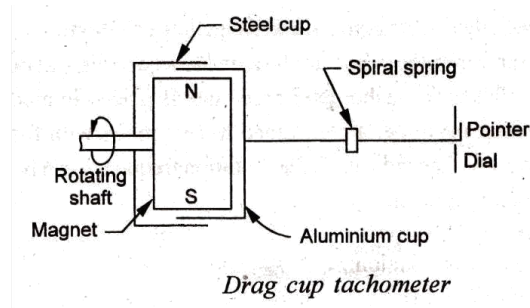
*Vibrating reed tachometer*

Tachometers of the vibrating reed type utilize the fact that speed and vibration in a body are interrelated. The instrument consists of a set of vertical reeds, each having its own natural frequency of vibration. The reeds are lined up in order of their natural frequency and are fastened to a base plate at one end, with the other end free to vibrate. When the tachometer base plate is placed in mechanical contact with the frame of a rotating machine, a reed tuned to resonance with the machine vibrations responds most frequently. The indicated reed vibration frequency can be calibrated to indicate the speed of the rotating machine.

## Electrical tachometers:

An electrical tachometer depends for its indications upon an electrical signal generated in proportion to the rotational speed of the shaft. Depending on the type of the transducer, electrical tachometers have been constructed in a variety of different designs.

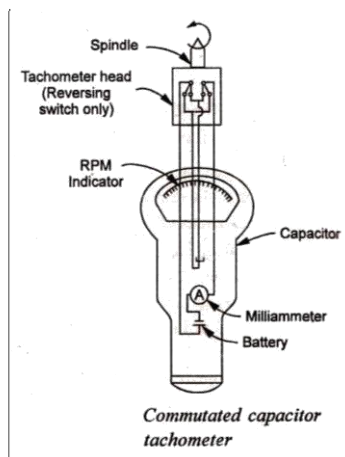
### 1. Drag cup tachometer:



In an eddy current or drag type tachometer, the test shaft rotates a permanent magnet and this induces eddy currents in a drag cup or disc held close to the magnet. The eddy currents produce a torque which rotates the cup against the torque of a spiral spring. The disc turns in the direction of the rotating magnetic field until the torque developed equals that of the spring. A pointer attached to the cup indicates the rotational speed on a calibrated scale. The automobile speedometers operate on this principle and measure the angular speed of the wheels. The rotational measurement is subsequently converted into linear measurement by assuming some average diameter of the wheel, and the scale is directly calibrated in linear speed units.

Eddy current tachometers are used for measuring rotational speeds upto 12,000 rpm with an accuracy of  $\pm 3\%$ .

### 2. Commutated capacitor tachometer:

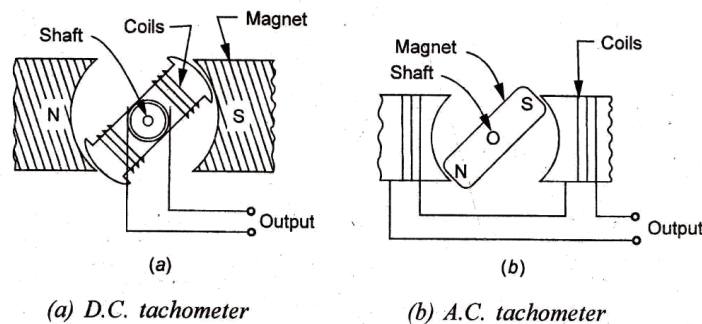


The operation of this tachometer is based on alternately charging and discharging a capacitor. These operations are controlled by the speed of the machine under test. The instrument essentially consists of:

h) Tachometer head containing a reversing switch, operated by a spindle which reverses twice with each revolution.

10. Indicating unit containing a voltage source, a capacitor, milliammeter and a calibrating circuit. When the switch is closed in one direction, the capacitor gets charged from d-c supply and the current starts flowing through the ammeter. When the spindle operates the reversing switch to close it in opposite direction, capacitor discharges through the ammeter with the current flow direction remaining the same. The instrument is so designed that the indicator responds to the average current. Thus, the indications are proportional to the rate of reversal of contacts, which in turn are proportional to speed of the shaft. The meter scale is graduated to read in rpm rather than in milliamperes. The tachometer is used within the range 200 - 10000 rpm.

**10).....Tachogenerators:** These tachometers employ small magnet type d.c or a.c generators which translate the rotational speeds into d.c. or a.c voltage signal. The operating principle of such tachometers is illustrated in Fig. Relative perpendicular motion between a magnetic field and conductor results in voltage generation in the conductor.



10) D. C. tachometer generator: This is an accurately made dc. generator with a permanent magnet of horse-shoe type. With rotation of the shaft, a pulsating dc. Voltage proportional to the shaft speed is produced, and measured with the help of a moving coil voltmeter having uniform scale and calibrated directly in terms of speed. The tachometer is sensitive to the direction of rotation and thus can be used to indicate this direction by the use of an indicator with its zero point at mid-scale. For greater accuracy, air gap of the magnetic paths must be maintained as uniform as possible. Further, the instrument requires some form of commutation which presents the problem of brush maintenance.

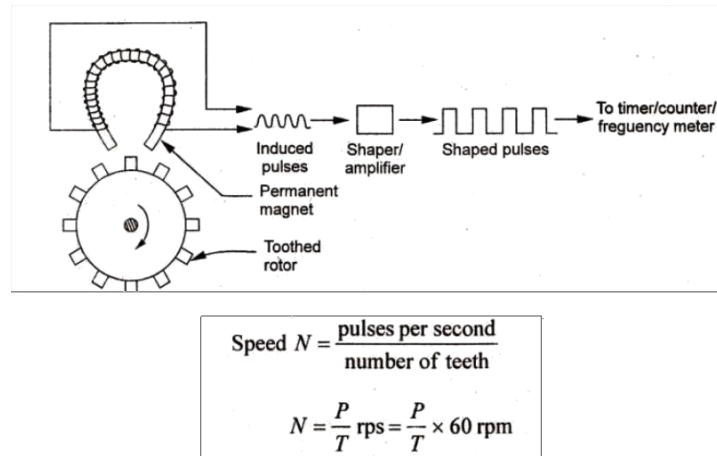
11) A.C. tachometer generator: The unit embodies a stator surrounding a rotating permanent magnet. The stator consists of a multiple pole piece (generally four), and the permanent magnet is installed in the shaft whose speed is being measured. When the magnet rotates, an a.c. voltage is induced in the stator coil. The output voltage is rectified and measured with a permanent magnet moving coil instrument. The instrument can also be used to measure a difference in speed of two sources by differentially connecting the stator coils.

Tachogenerators have been successfully employed for continuous measurement of speeds upto 500 rpm with an accuracy of  $\pm 1\%$ .

#### **4. Contactless electrical tachometers:**

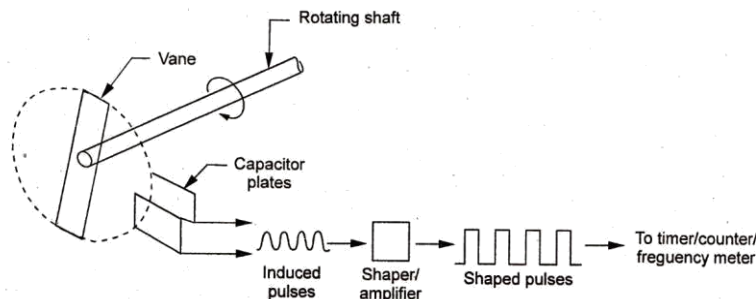
Tachometers of this type produce pulse from a rotating shaft without any physical contact between the speed transducer and the shaft. This aspect has the distinct advantage in that no load is applied to the machine.

⑦ Inductive pick-up tachometer: The unit consists of a small permanent magnet with a coil round it. This magnetic pick up is placed near a metallic toothed rotor whose speed is to be measured. As the shaft rotates, the teeth pass in front of the pick-up and produce a change in the reluctance of the magnetic circuit. The field expands or collapses and a voltage is induced in the coil. The frequency of the pulses depends upon the number of teeth on the wheel and its speed of rotation. Since the number of teeth is known, the speed of rotation can be determined by measuring the pulse frequency. To accomplish this task, pulse is amplified and squared, and fed into a counter of frequency measuring unit.



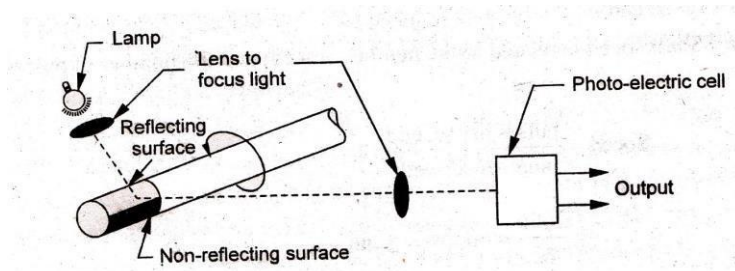
If the rotor has 60 teeth, and if the counter counts the pulses in one second, then the counter will directly display the speed in revolutions per minute.

(ii) Capacitive type pick-up tachometer:

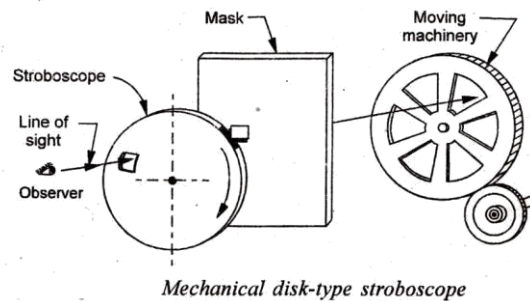


The device consists of a vane attached to one end of the rotating machine shaft. When the shaft rotates between the fixed capacitive plates, there occurs a change in the capacitance. The capacitor forms a part of an oscillator tank so that number of frequency changes per unit of time is a measure of the shaft speed. The pulses thus produced are amplified, and squared, and may then be fed to frequency measuring unit or to a digital counter so as to provide a digital analog of the shaft rotation.

23) Photo-electric tachometer: These pick-ups utilize a rotating shaft to intercept a beam of light falling on a photo-electric or photo conductive cell. The shaft has an intermittent reflecting (white) and non-reflecting (black) surface. When a beam of light hits the reflecting surface on the rotating shaft, light pulses are obtained and the reflected light is focused onto the photo-electric cell. The frequency of light pulses is proportional to the shaft speed, and so will be the frequency of electrical output pulses from the photo-electric cell.



#### (iv) Stroboscope:



The stroboscope utilises the phenomenon of vision when an object is viewed intermittently. The human sense of vision is so slow to react to light stimuli that it is unable to separate two different light impulses reaching the eye within a very short Period of time (less than 0.1second). A succession of impulses following one another at brief intervals are observed by the eye as a continuous unbroken sequence. A mechanical disk type stroboscope consists essentially of a whirling disk attached to motor whose speed can be varied and measured. A reference mark on the rotating shaft on the shaft appears to be stationary. For this condition, the shaft speed equals that of rotating disk, or some even multiple of this speed and is given by:

$$\text{Shaft speed} = \frac{(\text{disk speed}) \times (\text{number of openings in the disk})}{\text{number of images}}$$

✓

#### Vibration amplitude and acceleration

Vibration refers to the repeated cyclic oscillations of a system; the oscillatory motions may be simple harmonic (sinusoidal) or complex (non-sinusoidal). The oscillations are caused when acceleration is applied to the machine alternately in two directions

The excessive vibration level in a machine is an indication of the following troubles it can cause:

- o) Catastrophic failure as a result of stress caused by induced resonance and fatigue
- p) Excessive wear because of failure to compensate for vibration to which a product is subjected or which is created by the product
- q) Faulty production
- r) Incorrect operation of precision equipment and machinery because of failure to compensate for vibration and shock encountered in use

xvi. human discomfort leading to adverse effects such as motion sickness, breathing and speech disturbance, loss of touch of sensitivity etc.

Characteristics and units of vibrations: Vibration is generally characterized by

② The frequency in Hz, or

② The amplitude of the measured parameter which may be displacement, velocity or acceleration. Further, the units of vibration depend on the vibration parameter as follows:

(a) Displacement, measured in m, (b) velocity, measured in m/s and (c) acceleration, measured in  $m/s^2$ .

**Vibrating motions may be simple harmonic or complex. Assuming it to be simple harmonic,**

$$\text{displacement } x = A \sin \omega t$$

$$\text{velocity } v = \frac{dx}{dt} = A \omega \cos \omega t$$

$$\text{acceleration } a = \frac{dv}{dt} = -A \omega^2 \sin \omega t$$

where  $\omega = 2\pi f$  rad/s and  $f$  is the frequency of vibration in Hz. Obviously, the amplitude of the different parameters are :

$$\text{displacement amplitude} = A$$

$$\text{velocity amplitude} = A \omega$$

$$\text{acceleration amplitude} = A \omega^2$$

The measured amplitude is normally expressed in decibels with reference to a fixed value. Let  $A_1$  be the measured amplitude and  $A_0$  be the reference amplitude. Then the vibration level expressed in decibels is

$$\text{vibration level} = 20 \log_{10} \frac{A_1}{A_0} \text{ dB}$$

The internationally accepted reference values are:

(a) for velocity, the reference value is  $10^{-3}$  m/s, and

(b) for acceleration, the reference value is  $10^{-5}$  m/s<sup>2</sup>

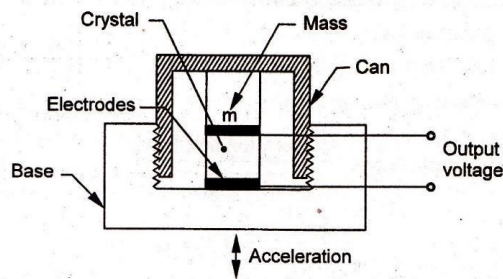
### **Measurement of acceleration:**

There are two types of accelerometers generally used for measurement of acceleration:

(i) Piezo-electric type, and (ii) seismic type.

(i) Piezo-electric accelerometer: The unit is perhaps the simplest and most commonly used transducer employed for measuring acceleration. The sensor consists of a piezo-electric crystal sandwiched, between two electrodes and has a mass placed on it. The unit is fastened to the base whose acceleration characteristics are to be obtained. The can threaded to the base acts as a 'spring and squeezes the mass against the crystal. Mass exerts a force on the crystal and a certain output voltage is generated. If the base is now accelerated downward, inertial reaction force on the base acts upward against the top of the can. This relieves stress on the crystal. From Newton's second law

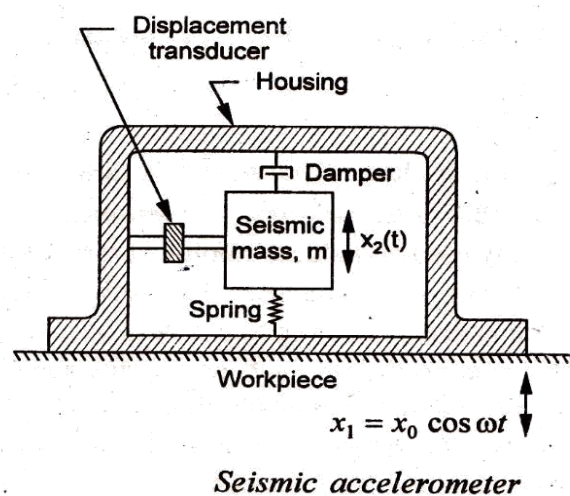
$$\text{force} = \text{mass} \times \text{acceleration}$$



#### Advantages and limitations

- 15) Rugged and inexpensive device
- 16) High output impedance '
- 17) High frequency response from 0.10 Hz to 50 kHz
- 18) High sensitivity varies from 10 to 100 mV/g where  $g = 9.807 \text{ m/s}^2$
- 19) Capability to measure acceleration from a fraction of  $g$  to thousands of  $g$
- 20) Somewhat sensitive to changes in temperature
- 21) Subject to hysteresis errors.

Displacement sensing (seismic) accelerometer: In a seismic accelerometer the displacement of a mass resulting from an applied forced is measured and correlated to the acceleration. Fig shows the schematics of a common spring mass damper system which accomplishes this task. The mass is supported by a spring and damper is connected to the housing frame. The frame is rigidly attached to the machine whose acceleration characteristics are to be determined. When an acceleration is imparted by the machine to the housing frame, the mass moves relative to the frame, and this relative displacement between the mass and frame is sensed and indicated by an electrical displacement transducer.





**Theory of seismic accelerometer :** The spring-mass-damper system of the seismic accelerometer can be represented by an equilibrium equation obtained through Newton's second law :

$$m \frac{d^2 x_2}{dt^2} + c \frac{dx_2}{dt} + kx_2 = c \frac{dx_1}{dt} + kx_1 \quad \dots(12.14)$$

where the damping force has been assumed to be proportional to the velocity. For a simple harmonic vibratory motion applied to the housing frame,

$$\text{displacement } x_1 = A \cos \omega t$$

$$\text{velocity } v = \frac{dx_1}{dt} = -\omega A \sin \omega t$$

$$\text{acceleration } a = \frac{dv}{dt} = -\omega^2 A \cos \omega t \quad \dots(12.15)$$

where  $\omega = 2\pi f$  rad/s and  $f$  is the frequency of vibration in Hz. From these expressions for the instantaneous values of different parameters we have :

$$\text{displacement amplitude} = A$$

$$\text{velocity amplitude} = \omega A$$

$$\text{acceleration amplitude} = \omega^2 A \quad \dots (12.16)$$

A solution to equation 12.14 would show that the relative displacement  $(x_2 - x_1)$  between the mass and housing is given by :

$$(x_2 - x_1) = \frac{\omega^2 A}{\omega_n^2 \left[ \left\{ 1 - \left( \frac{\omega}{\omega_n} \right)^2 \right\}^2 + \left\{ 2 \left( \frac{c}{c_c} \right) \left( \frac{\omega}{\omega_n} \right) \right\}^2 \right]^{\frac{1}{2}}} \quad \dots(12.17)$$

where the natural frequency  $\omega_n$  and critical damping coefficient  $c_c$  are given by

$$\omega_n = \sqrt{\frac{k}{m}} \quad ; \quad c_c = 2 \sqrt{mk} \quad \dots(12.18)$$

The seismic instrument may be used either for displacement measurement by proper selection of the mass-spring-damper combination. Since velocity is rate of change of displacement and acceleration is rate of change of velocity, each quantity can be obtained by differentiating or integrating one of the quantity which has been measured. Since the process of integration is more common and easily done in electrical systems, it is a common practice to measure acceleration and then deduce the velocity or displacement by successive integration.

**Displacement measurement :** Let the frequency ( $\omega$ ) applied to the base be much higher than the natural frequency ( $\omega_n$ ), then the term  $\{2(c/c_c)(\omega/\omega_n)\}^2$  can be neglected in comparison with  $\left[(\omega/\omega_n)^2\right]^2$  and the approximate expression for  $(x_2 - x_1)$  becomes :

$$(x_2 - x_1) = \frac{\omega^2 A}{\omega_n^2 \left[ \left\{ \left( \frac{\omega}{\omega_n} \right)^2 \right\}^2 \right]^{\frac{1}{2}}} = \frac{\omega^2 A}{\omega_n^2 \left( \frac{\omega}{\omega_n} \right)^2} = A \quad \dots(12.19)$$

Thus the output is very nearly equal to the input amplitude  $A$ . This relation is valid for  $\omega/\omega_n$  ratios greater than 2. Thus for vibration pick-ups, the system is to be operated at frequencies higher than the natural frequency. The task is accomplished by keeping the natural frequency ( $\omega_n = \sqrt{k/m}$ ) low by employing soft spring and large mass.

**Acceleration measurement :** Let the input frequency  $\omega$  be much smaller than the natural frequency  $\omega_n$ , then

$$(x_2 - x_1) = \frac{\omega^2 A}{\omega_n^2} = \frac{1}{\omega_n^2} \times \text{maximum acceleration} \quad \dots(12.20)$$

and this relation remains valid for  $\omega/\omega_n \leq 0.4$ . This if the pick-up is to be used for acceleration measurement,  $\omega_n$  should be large, i.e., the system should have a stiff spring and small mass. That would enable to operate the system over a wide range of frequencies and still keep the response linear.

In a **strain gauge accelerometer** (Fig. 12.25), the sensing mass is mounted on a cantilever beam. A viscous liquid fills the housing and provides the necessary damping. Two strain gauges are attached to the beam, one on each and these sense the strain in the

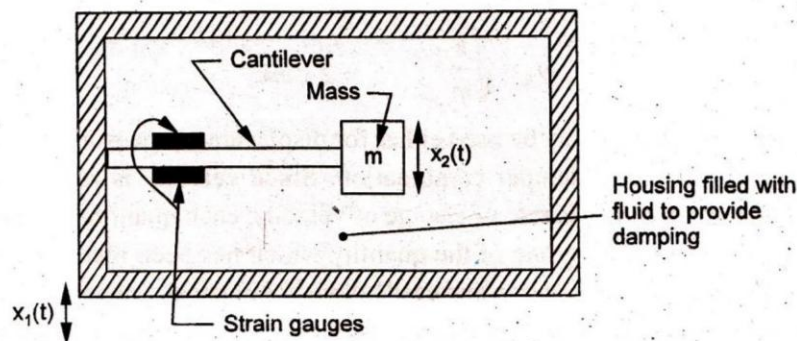


Fig. 12.25 Strain gauge accelerometer

beam which results from vibratory displacement. The leads from the strain gauges are taken to a wheatstone bridge whose output indicates the relative displacement between the mass and the housing form.

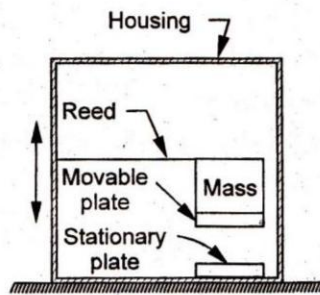


Fig. 12.26 (a)  
Capacitance vibration sensor

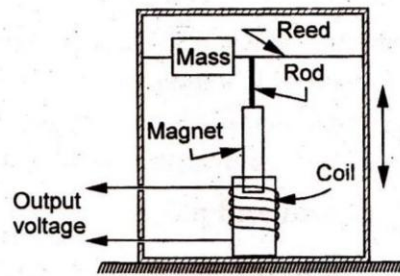


Fig. 12.26 (b)  
Inductive vibration sensor

Quite often, vibration amplitudes are translated into an inductance and capacitance change of the system. Magnitude of the output voltage or capacitance is then taken as a measure of the amplitude of vibration. The schematics of such vibration pick-ups are shown in Fig. 12.26 which are self-explanatory.

A suitable estimate of frequency and amplitude of vibrations in light systems (where it is not possible to attach an electrical transducer) is best made by using either a stroboscope or a reed vibrometer.

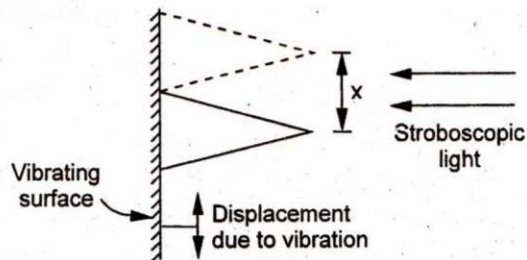


Fig. 12.27 Stroboscopic method for vibration measurement

A fixed pointer is attached to the vibrating surface (Fig. 12.27), flashes from a stroboscope are directed onto the pointer and frequency of light flashes is adjusted until a

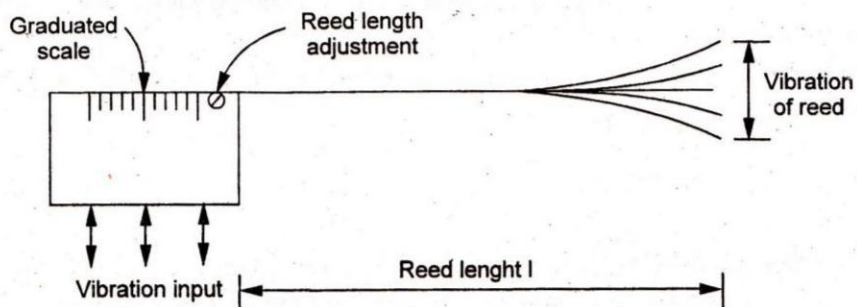


Fig. 12.28 Reed vibrometer



stationary image or a slowly moving image of the pointer is obtained. The flash frequency is then related to the amplitude or frequency of vibration. The stroboscope method is quite suitable for small-amplitude vibrations having an upper frequency range of about 500 Hz.

The reed vibrometer employs a reed which is mounted onto the vibrating structure or mechanism. The length of the reed is adjusted so that its natural frequency is equal to the frequency of the vibrating surface. Under this resonance condition, the reed vibrates with maximum amplitude. The reed length is calibrated directly in frequency units ; typical range of frequency measurement is 5 Hz to 10000 Hz.

#### **UNIT-IV**

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# Strain and Stress: Measurement and Analysis

*www.jntuworld.com // www.jwjobs.net*

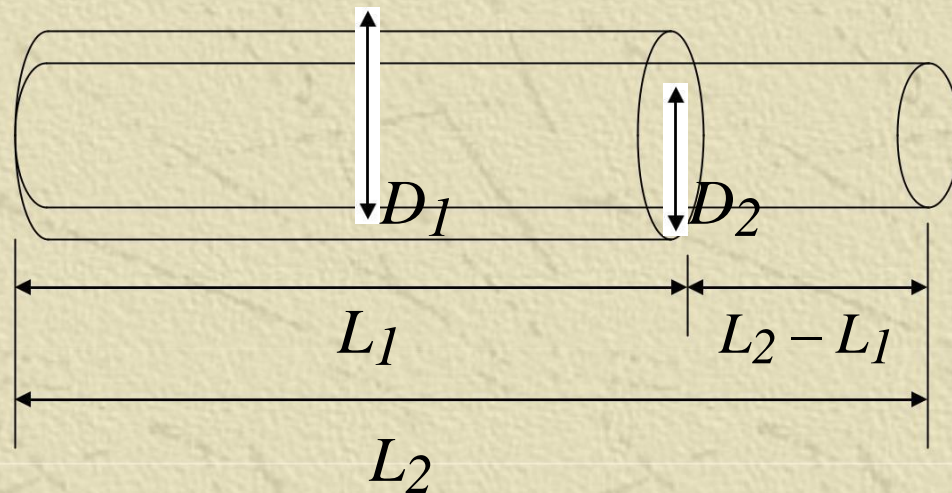


$$12. \quad \epsilon_a = dL / L \approx (L_2 - L_1) / L_1 = \Delta L / L$$

$\epsilon_a$  = axial strain

$L_1$  = linear dimension or gage length

$L_2$  = final strained linear dimension





$$13. \quad \sigma_a$$

$a$

$E$  = Young's modulus

$\sigma_a$  = uniaxial stress

$$= \frac{\epsilon_L}{a}$$

$a$

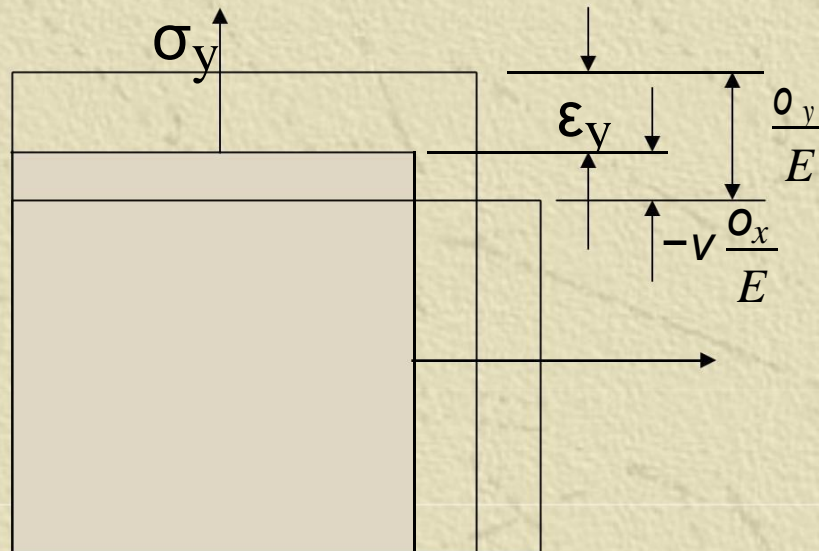
$\nu$  = Poisson's ratio

$\epsilon_L$  = lateral strain

$$\sigma_x - \nu \sigma_y$$

$$\epsilon_x = \frac{\sigma_x - \nu \sigma_y}{E} \quad \epsilon_y = \frac{\sigma_y - \nu \sigma_x}{E}$$

$$\sigma_x = \frac{E(\epsilon_x + \nu \epsilon_y)}{1 - \nu^2} \quad \sigma_y = \frac{E(\epsilon_y + \nu \epsilon_x)}{1 - \nu^2}$$





# Strain Measurement



## Extensometer

- Optical

- Mechanical



## Electrical strain gage

- Resistive – the most common

- Capacitive

- Inductive

- Photoelectric

# Electrical Resistance Strain Gage

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1856 Lord Kelvin demonstrated that the resistances of copper wire and iron wire change when the wires are subjected to mechanical strain

He used a Wheatstone bridge circuit with a galvanometer as the indicator





The first resistance strain gage is made by Carlson in 1931

■ Pillars were mounted, separated by the gage length, with wires stretched between them



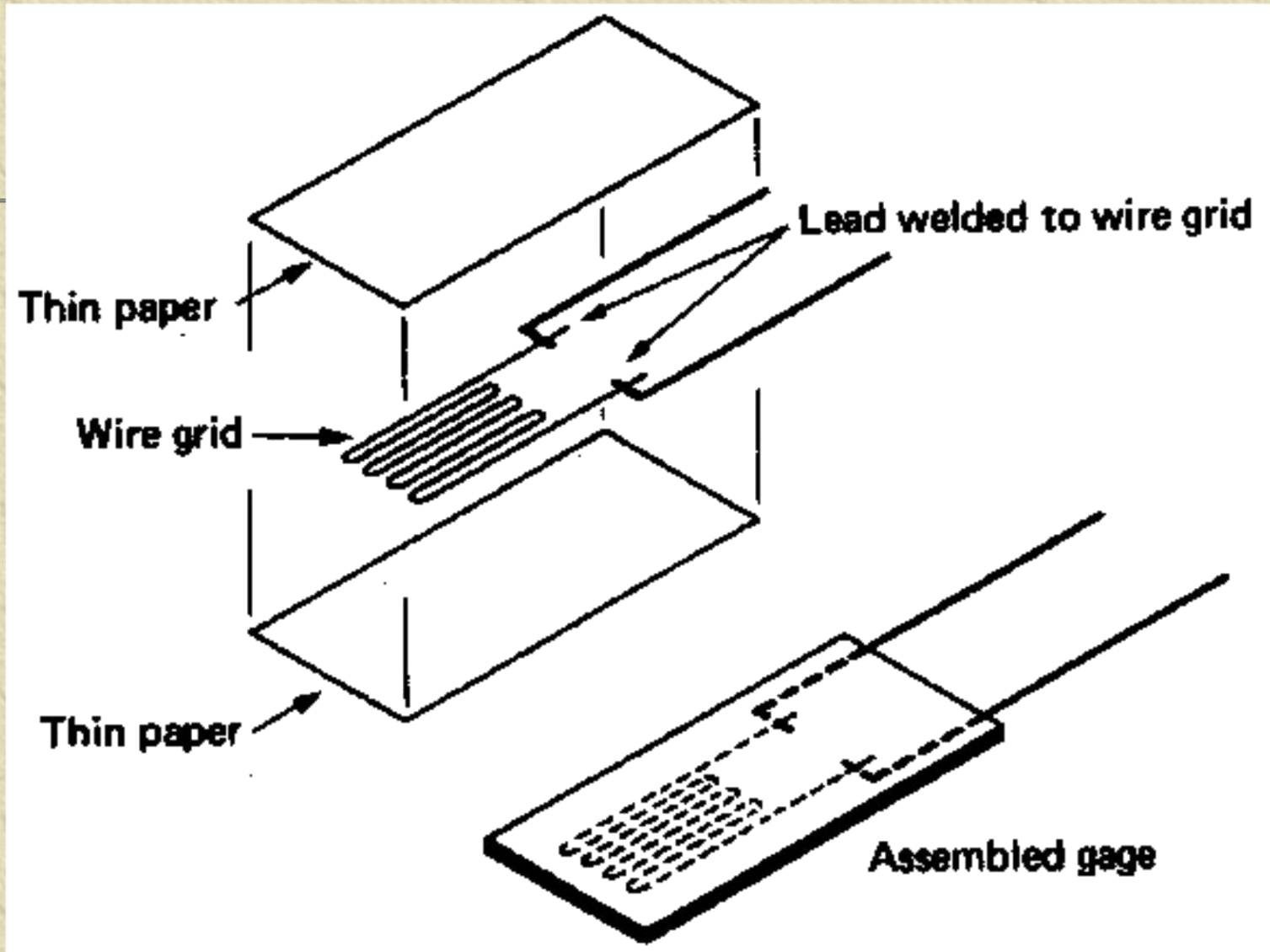
The first bonded strain gage was used by Bloach

■ It consisted of a carbon film resistance element applied directly to the surface of the strained member



1938 Ruge of M.I.T. conceived the idea of making a preassembly by mounting wire between thin pieces of paper





Construction of bonded-wire-type strain gage

# Foil-Type Gage



During the 1950s the foil-type gage replaced the the wire gage



The common form consists of a metal foil element on a thin epoxy support

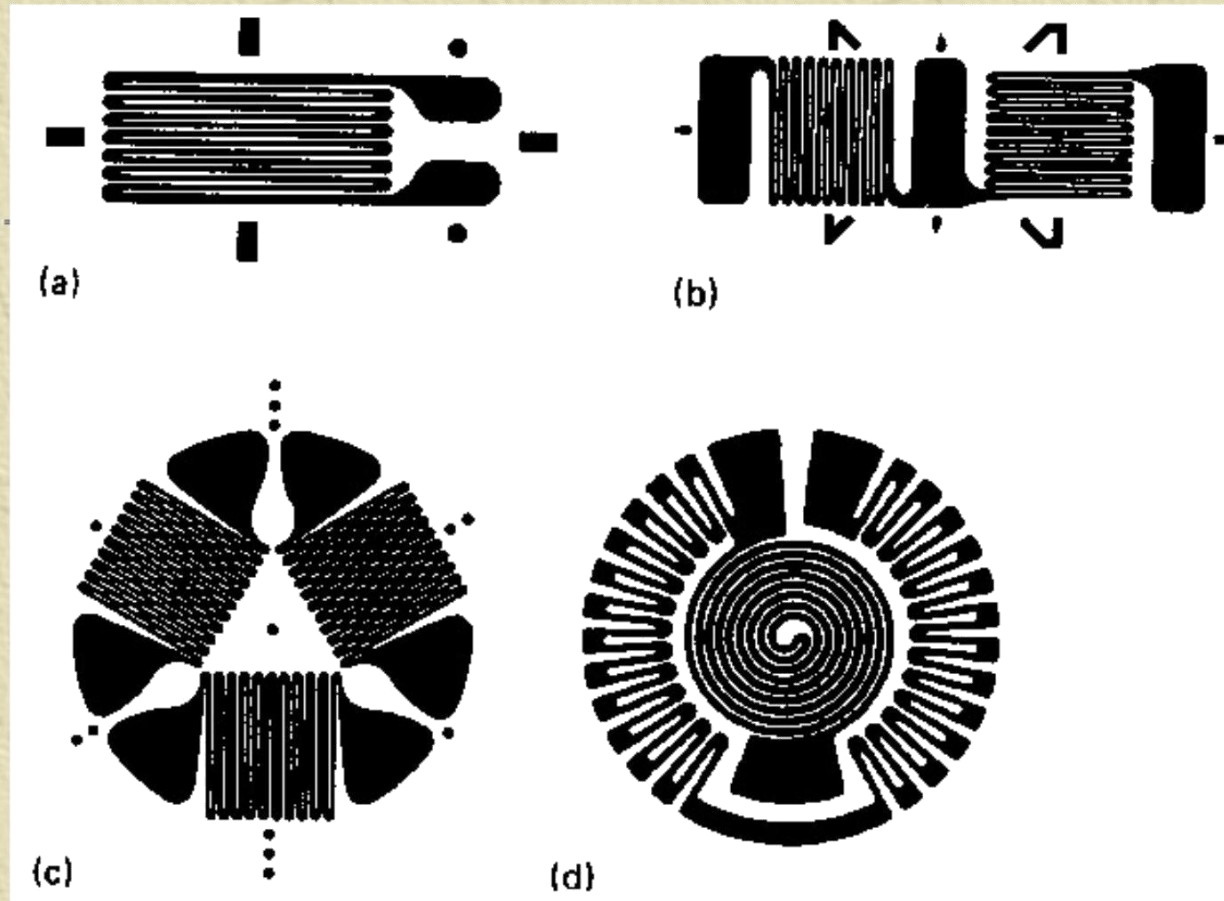


Manufactured using printed-circuit techniques



Major advantage – almost unlimited pane configurations are possible





Typical foil-type gages illustrating the following types:  
(a) single element, (b) two-element rosette, (c) three-element rosette, (d) one example of many different special purpose gages (for pressurized diaphragms)

$$R = \frac{\rho L}{A} = \frac{\rho L}{CD^2}$$

The *gage factor*

$$F = \frac{dR / R}{dL / L} = \frac{dR / R}{\epsilon_a} = 1 + 2\nu + \frac{d\rho / \rho}{dL / L}$$

$$i) = -1 \frac{\Delta R}{F R}$$

The values of  $F$  and  $R$  are supplied by the gage manufacturer, and the user determines  $\Delta R$  corresponding to the input situation being measured.





# Selection and Installation Factors for Bonded Metallic Strain Gages

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Grid material and configuration



Backing material



Bonding material and method









Gage protection



Associated electrical circuitry

# Desirable Properties of Grid Material

- 
-  High gage factor,  $F$
  -  High sensitivity,  $\rho$
  -  Low temperature sensitivity
  -  High electrical stability
  -  High yield strength
  -  High endurance limit





Good workability



Good solderability or weldability



Low hysteresis



Low thermal emf when joined to  
other materials



Good corrosion resistance





# Temperature Sensitivity



In many applications, compensation is provided in the electrical circuitry – this does not always eliminate the problem



Two factors are involved:

-  The differential expansion existing between the grid support and the grid proper, resulting in a strain that the gage is unable to distinguish from load strain
-  The change in resistivity  $\rho$  with temperature change

# Thermal emf Effect



Thermal emf superimposed on gage output must be avoided if dc circuitry is used



For ac circuitry this factor would be of little importance





# Common Grid Materials



Constantan\*; Copel\* 45% Ni, 55% Cu



Isoelastic\* 36% Ni, 8% Cr, 0.5% Mo, Fe  
remainder

\*Trade names



# Common Backing Materials

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Thin paper



Phenolic-impregnated paper



Epoxy-type plastic films



Epoxy-impregnated fiberglass



Most foil gages use an epoxy film backing



# Protecting the Strain Gage

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The strain gages must be protected from ambient conditions:

- Mechanical abuse, moisture, oil, dust and dirt



Protection material:

- Petroleum waxes, silicone resins, epoxy preparations, rubberized brushing compounds





# Temperature Compensation

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The adjacent-arm compensating gage –  
bridge circuitry



Self-temperature compensation



Selected-melt gage

11. Through proper manipulation of alloy and processing, grid materials may be prepared to show very low apparent strain versus temperature change



Dual-element gage

- 11) Use two wire elements connected in series in one gage assembly
- 12) The two elements have different temperature characteristics and are selected so that the net temperature-induced strain is minimized



# Strain-Measuring Systems

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Basic strain indicator, useful for static: single-channel readings



Single-channel system either external to or an integral part of a cathode-ray oscilloscope



Oscillographic systems incorporating either  
12) stylus-and-paper or lightbeam  
and photographic paper readout





## Data acquisition systems:

- Displayed (digitally and/or by a video terminal)
- Recorded (magnetic tape or hard-copy printout)
- Fed back into the system for control purpose

# Stress-Strain Relationships



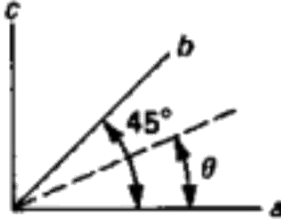
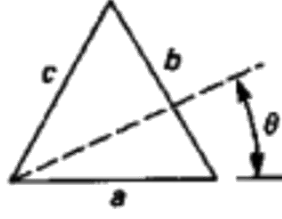
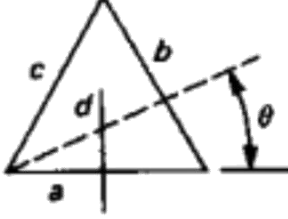
Simple uniaxial stress situation



Biaxial stress situation

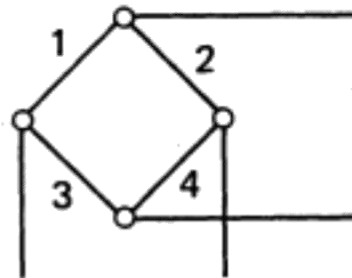


# Stress-strain relations for Rosette gages (T 12.4)

Type of Rosette:	 <b>Rectangular</b>	 <b>Equiangular (delta)</b>	 <b>T-delta</b>
Principal strains, $\epsilon_1, \epsilon_2$	$\frac{1}{2} \left[ \epsilon_a + \epsilon_c \pm \sqrt{2(\epsilon_a - \epsilon_b)^2 + 2(\epsilon_b - \epsilon_c)^2} \right]$	$\frac{1}{3} \left[ \epsilon_a + \epsilon_b + \epsilon_c \pm \sqrt{2(\epsilon_a - \epsilon_b)^2 + 2(\epsilon_b - \epsilon_c)^2 + 2(\epsilon_c - \epsilon_a)^2} \right]$	$\frac{1}{2} \left[ \epsilon_a + \epsilon_d \pm \sqrt{(\epsilon_a - \epsilon_d)^2 + \frac{4}{3}(\epsilon_b - \epsilon_c)^2} \right]$
Principal stresses, $\sigma_1, \sigma_2$	$\frac{E}{2} \left[ \frac{\epsilon_a + \epsilon_c}{1 - \nu} \pm \frac{1}{1 + \nu} \sqrt{2(\epsilon_a - \epsilon_b)^2 + 2(\epsilon_b - \epsilon_c)^2} \right]$	$\frac{E}{3} \left[ \frac{\epsilon_a + \epsilon_b + \epsilon_c}{1 - \nu} \pm \frac{1}{1 + \nu} \sqrt{2(\epsilon_a - \epsilon_b)^2 + 2(\epsilon_b - \epsilon_c)^2 + 2(\epsilon_c - \epsilon_a)^2} \right]$	$\frac{E}{2} \left[ \frac{(\epsilon_a + \epsilon_d)}{1 - \nu} \pm \frac{1}{1 + \nu} \sqrt{(\epsilon_a - \epsilon_d)^2 + \frac{4}{3}(\epsilon_b - \epsilon_c)^2} \right]$
Maximum shear, $\tau_{max}$	$\frac{E}{2(1 + \nu)} \sqrt{2(\epsilon_a - \epsilon_b)^2 + 2(\epsilon_b - \epsilon_c)^2}$	$\frac{E}{3(1 + \nu)} \sqrt{2(\epsilon_a - \epsilon_b)^2 + 2(\epsilon_b - \epsilon_c)^2 + 2(\epsilon_c - \epsilon_a)^2}$	$\frac{E}{2(1 + \nu)} \sqrt{(\epsilon_a - \epsilon_d)^2 + \frac{4}{3}(\epsilon_b - \epsilon_c)^2}$
$\tan 2\theta$	$\frac{2\epsilon_b - \epsilon_a - \epsilon_c}{\epsilon_a - \epsilon_c}$	$\frac{\sqrt{3}(\epsilon_c - \epsilon_b)}{(2\epsilon_a - \epsilon_b - \epsilon_c)}$	$\frac{2}{\sqrt{3}} \frac{(\epsilon_c - \epsilon_b)}{(\epsilon_a - \epsilon_d)}$
$0 < \theta < +90^\circ$	$\epsilon_b > \frac{\epsilon_a + \epsilon_c}{2}$	$\epsilon_c > \epsilon_b$	$\epsilon_c > \epsilon_b$

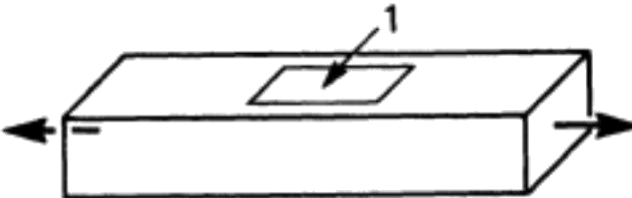
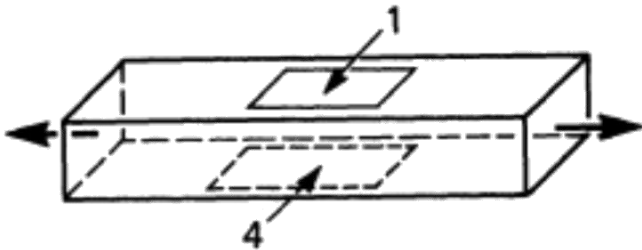
# Gage Orientation and Interpretation of Results

## Standard Bridge Configuration

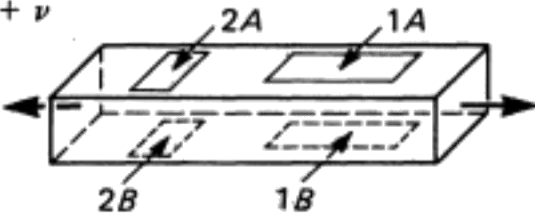
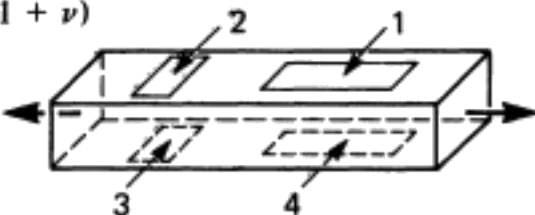
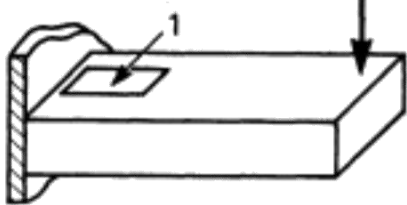
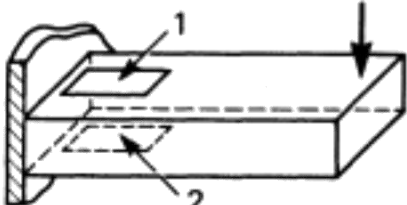



**Requirement for null:**  $R_1/R_2 = R_3/R_4$

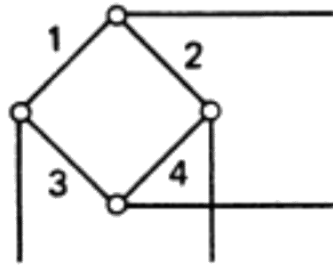
$$K = \text{Bridge constant} = \frac{\text{Output of bridge}}{\text{Output of primary gage}}$$

A	<p><math>K = 1</math></p> 	<p>Compensates for temperature if “dummy” gage is used in arm 2 or arm 3.</p> <p>Does not compensate for bending.</p>
B	<p><math>K = 2</math></p> 	<p>Compensates for bending.</p> <p>Two-arm bridge does not provide temperature compensation.</p> <p>Four-arm bridge (“dummy” gages in arms 2 and 3) provides temperature compensation.</p>



C	$K = 1 + \nu$ 	<p>Two-arm bridge compensates for temperature and bending.</p>
D	$K = 2(1 + \nu)$ 	<p>Four-arm bridge compensates for temperature and bending.</p>
E	$K = 1$ 	<p>Temperature compensation accomplished when "dummy" gage is used in arm 2 or arm 3.</p> <p>Bridge is also sensitive to axial and torsional components of loading.</p>
F	$K = 2$ 	<p>Temperature effects and axial and torsional components are compensated.</p>
G	$K = 4$ 	<p>Four-arm bridge.</p> <p>Temperature effects and axial and torsional components are compensated.</p>

## Standard Bridge Configuration

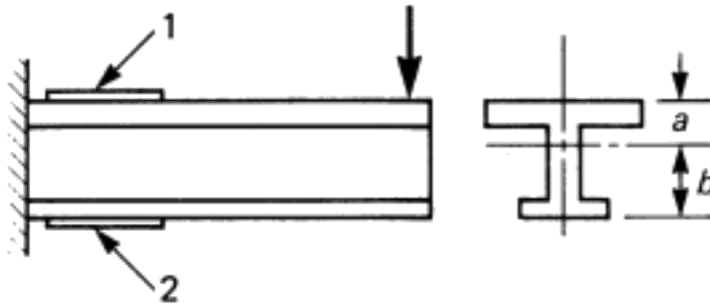


Requirement for null:  $R_1/R_2 = R_3/R_4$

$K = \text{Bridge constant} = \frac{\text{Output of bridge}}{\text{Output of primary gage}}$

$$K = (a + b)/a$$

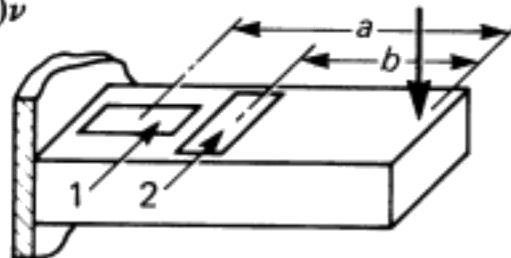
*H*



Temperature effects and axial and torsional components are compensated.

$$K = 1 + (b/a)\nu$$

*I*

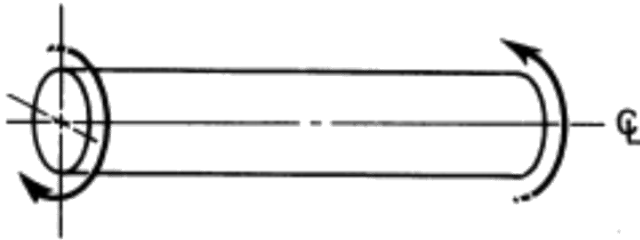


Temperature effects are compensated.

Axial and torsional load components are not compensated.

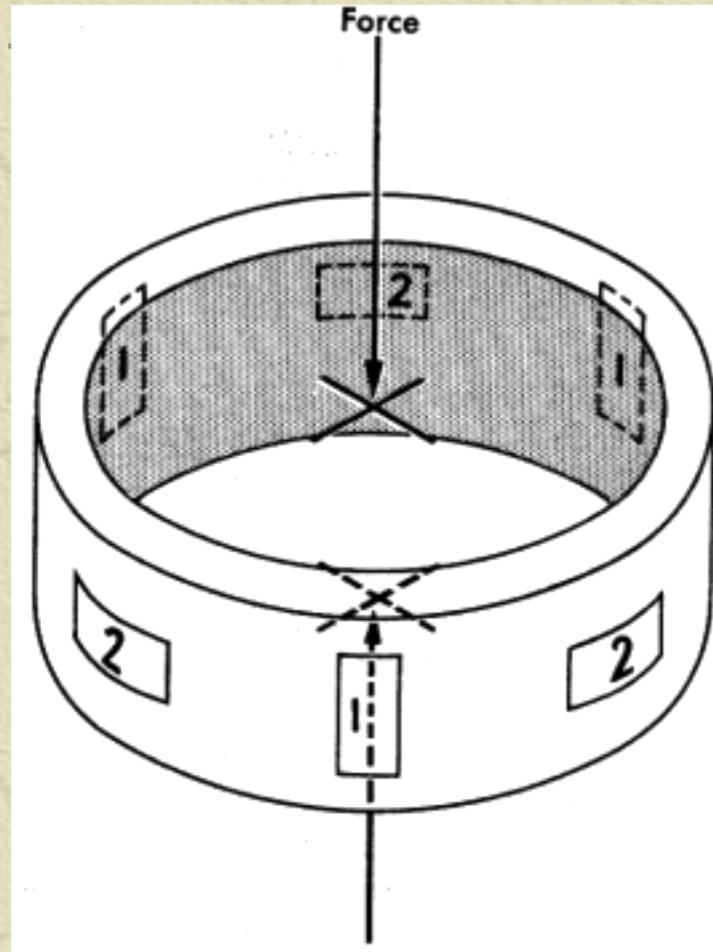


## Torsion



$J$	$K = 2$		<p>Two-arm bridge.</p> <p>Temperature and axial load components are compensated.</p> <p>Bending components are accentuated.</p>
$K$	$K = 2$		<p>Two-arm bridge.</p> <p>Temperature effects and axial load components are compensated.</p> <p>Relatively insensitive to bending.</p>
$L$	$K = 4$		<p>Four-arm bridge.</p> <p>Sensitive to torsion only.</p> <p>(Gages 1 and 3 are on opposite sides of the shaft from gages 2 and 4.)</p>

# Gages Connected in Series



Load cell employing three series-connected axial gages and three series-connected Poisson-ratio gages



# Measurement of Force



Mechanical weighing systems

Balance, multiple-lever system, pendulum force-measuring mechanism



Elastic transducers

Proving ring



Strain-gage load cells

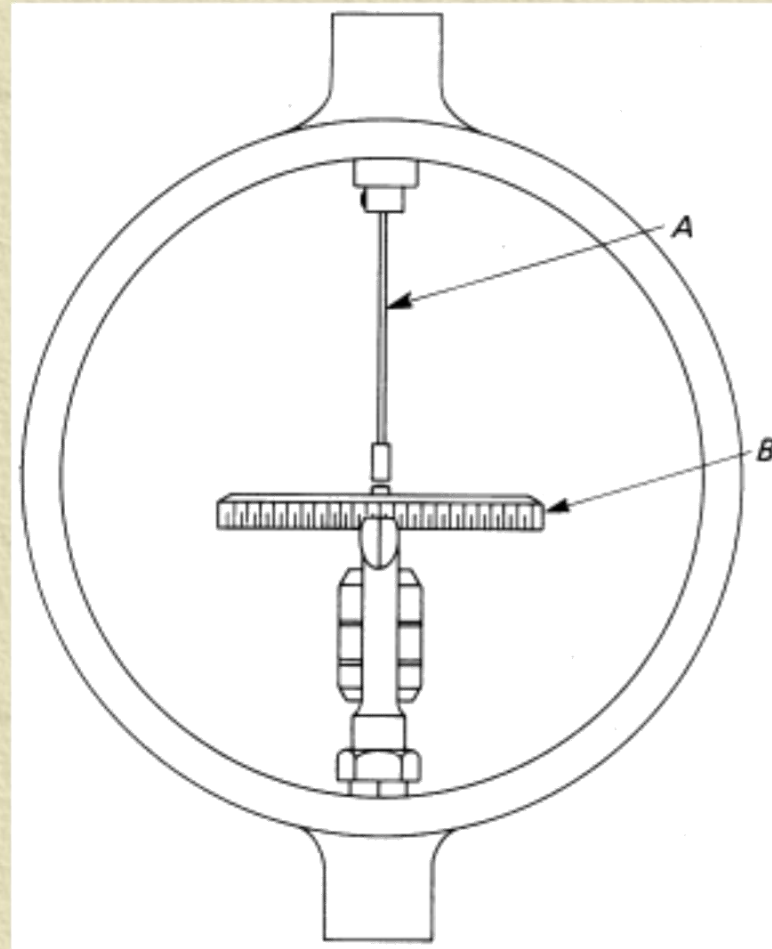


Piezoelectric-type load cells



Hydraulic and pneumatic systems

# Proving Ring



Compression-type proving ring with vibrating reed





Deflection is used as the measure of applied load, with the deflection measured by means of a precision micrometer

# Strain-Gage Load Cells

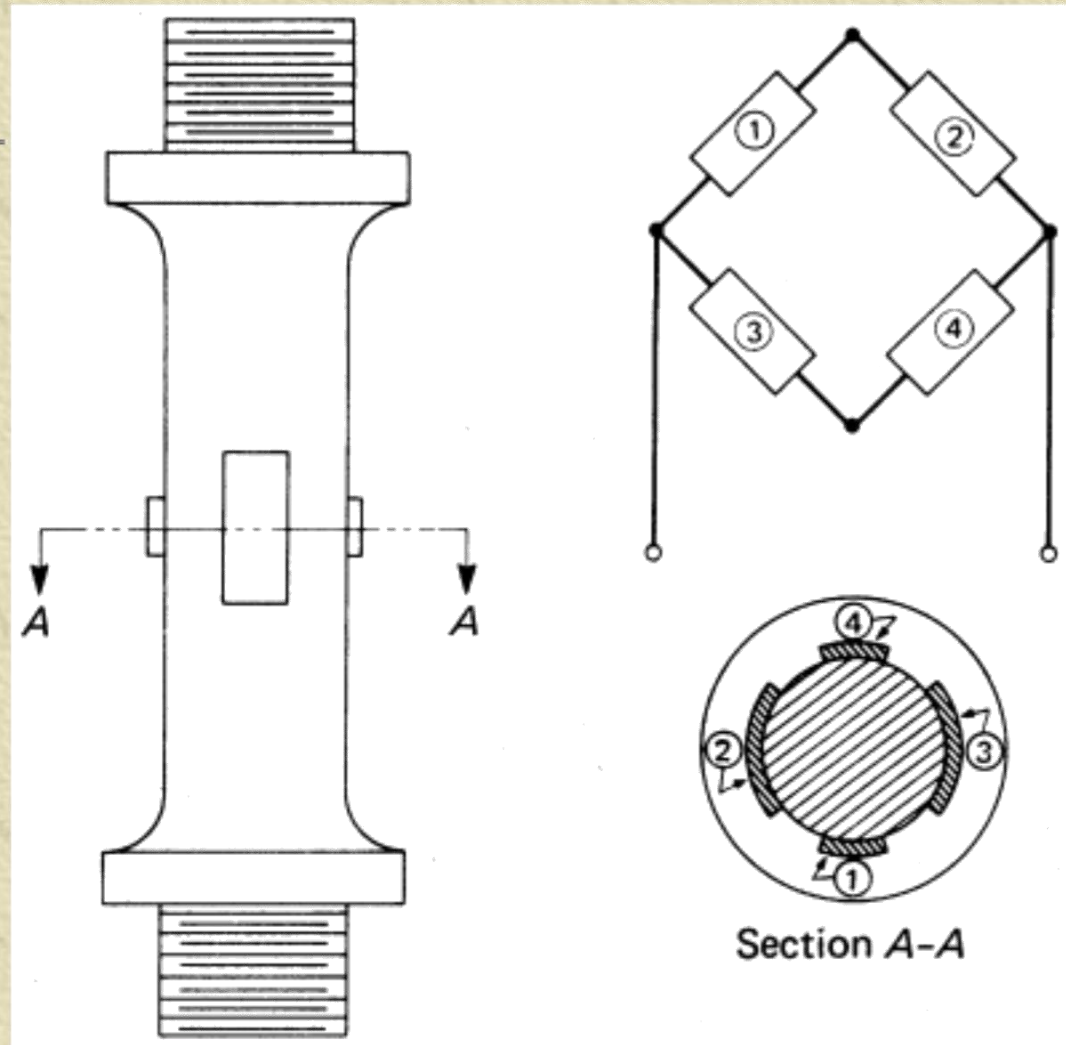


Measures load in terms of unit strain



One of the possible forms of elastic member is selected, and the gages are mounted to provide maximum output



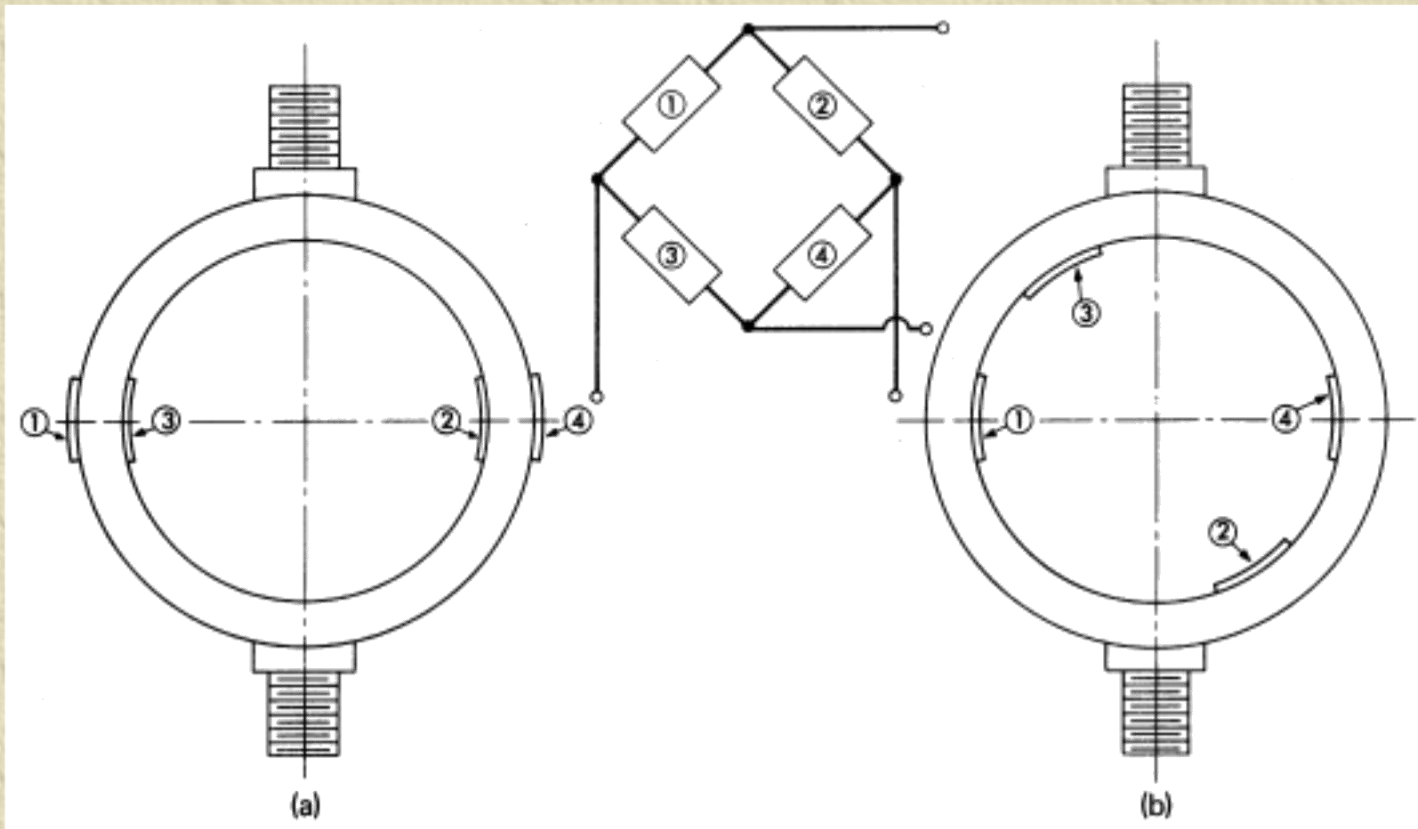


Tension-compression resistance strain-gage load cell



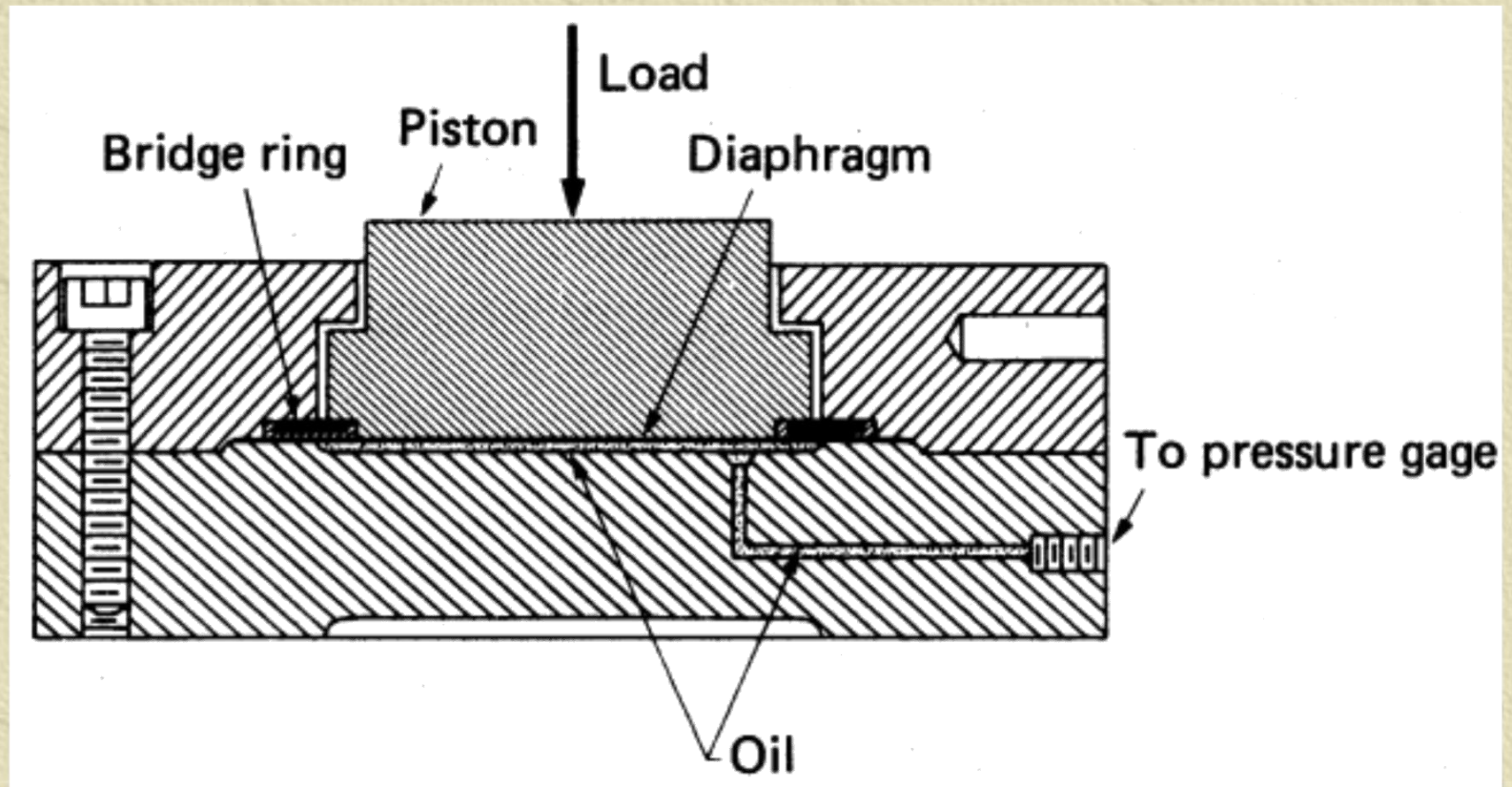
(a) The bridge output is a function of the bending strains only, the axial components being canceled in the bridge arrangement

(b) Greater sensitivity may be obtained because the output includes both the bending and the axial components sensed by gages 1 and 4



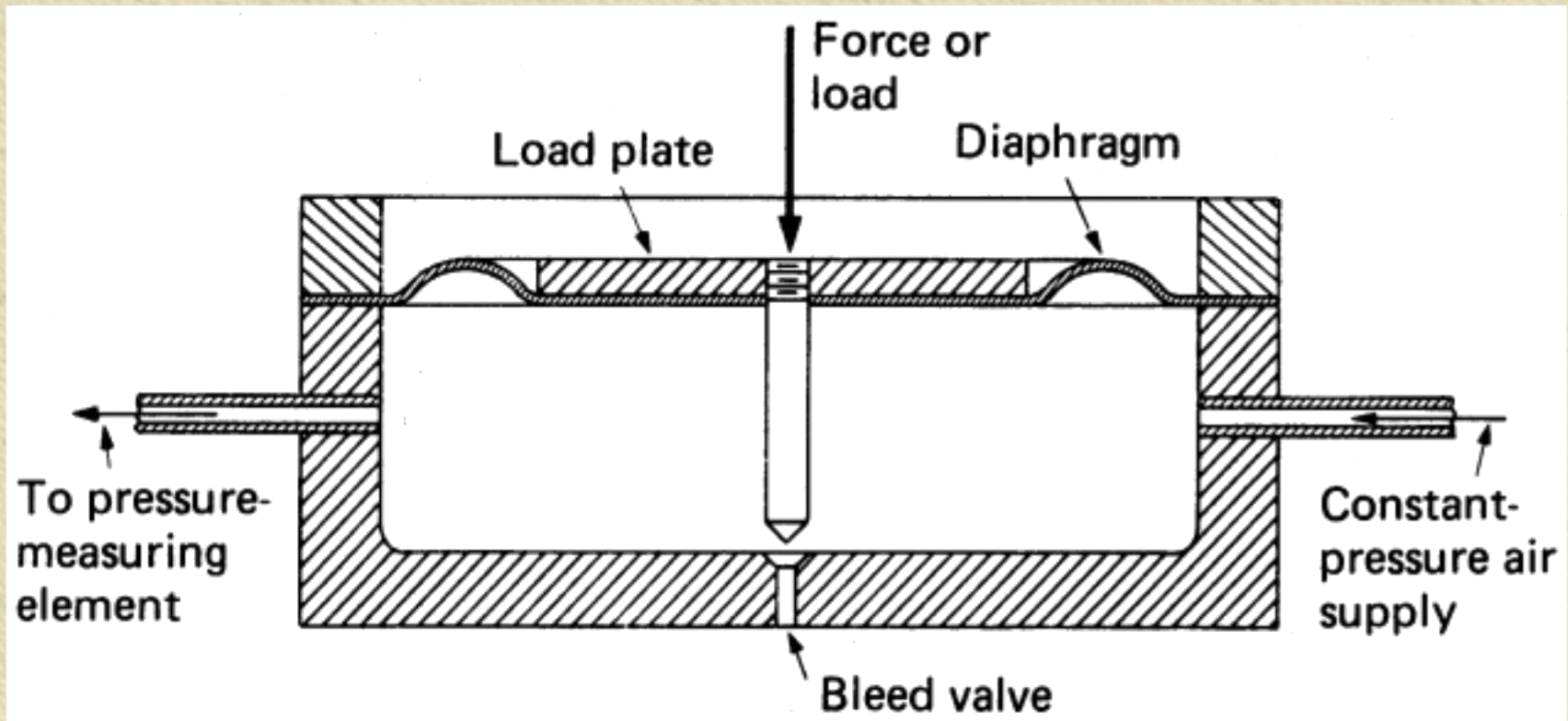
Two arrangements of circular-shaped load cells employing resistance strain gages as secondary transducers

# Hydraulic Load Cell

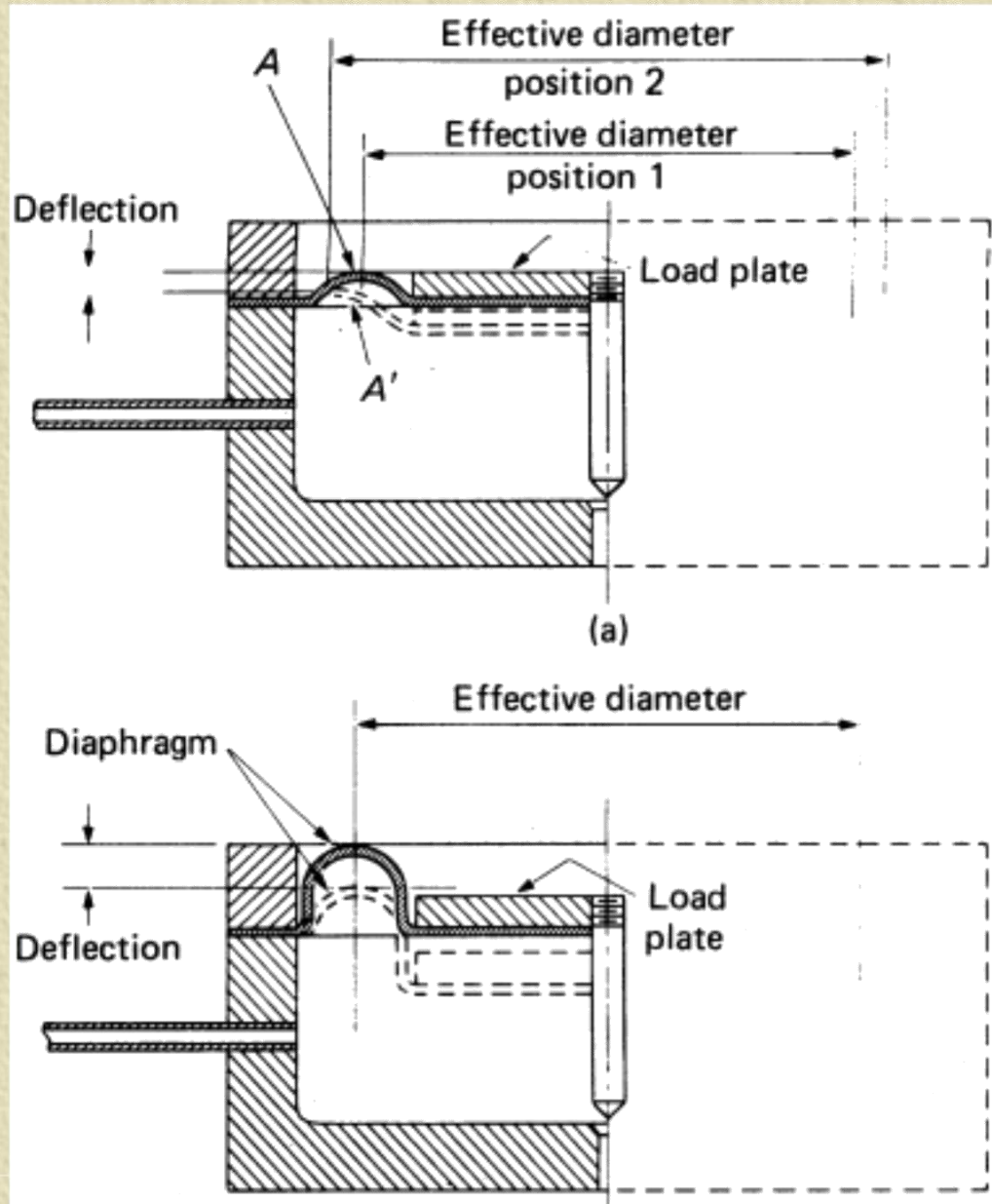


Section through a hydraulic load cell





Section through a pneumatic load cell



- (a) Section through a diaphragm showing how a change in effective area may take place.
- (b) When sufficient “roll” is provided, the effective area remains constant



# Pneumatic Load Cell



Use air rather than liquid as the pressurized medium



Use diaphragms of a flexible material rather than pistons





Designed to regulate the balancing pressure automatically

- Air pressure is supplied to one side of the diaphragm and allowed to escape through a position-controlling bleed valve
- The pressure under the diaphragm is controlled both by source pressure and bleed valve position
- The diaphragm seeks the position that will result in just the proper air pressure to support the load

# Measurement of Pressure



Absolute pressure



Gage pressure



Vacuum



# Pressure-Measuring Transducers



## Gravitational types

- Liquid columns

- Pistons or loose diaphragm, and weights



## Direct-acting elastic types

- Unsymmetrically loaded tubes

- Symmetrically loaded tubes

- Elastic diaphragms

- Bellows

- Bulk compression



Direct-acting elastic type, a piston with elastic restraining member



# Elastic Diaphragms

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Use elastic diaphragm as primary pressure transducer



Flat type –

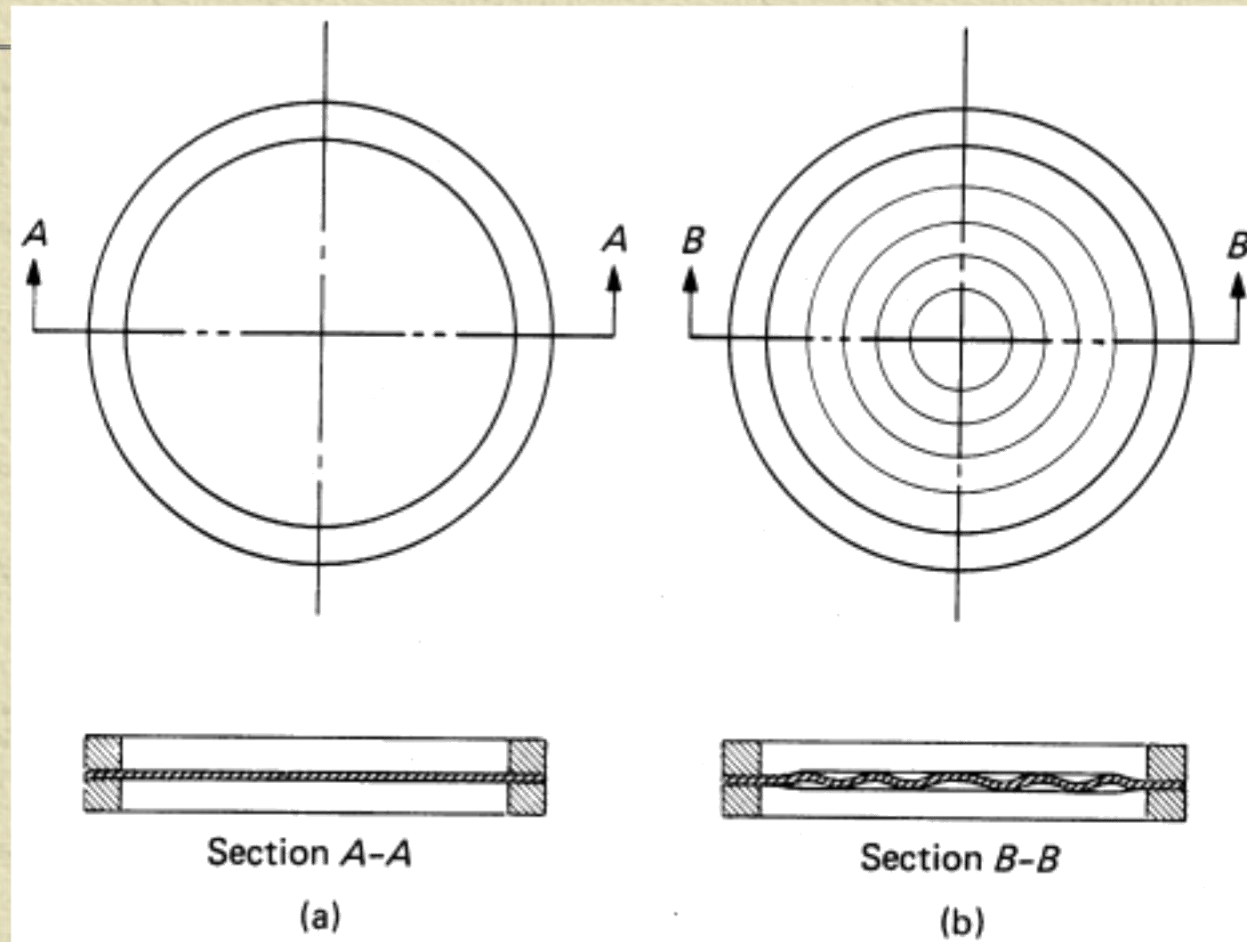


Used in conjunction with electrical secondary transducers whose sensitivity permits quite small diaphragm deflections



Corrugated type is particularly useful when larger deflections are required





(a) Flat diaphragm (b) Corrugated diaphragm

# Diaphragm Design Requirements

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Dimensions and total load must be compatible with physical properties of the material used



Flexibility must be such as to provide the sensitivity required by the secondary transducer



Volume of displacement should be minimized to provide reasonable dynamic response





Diaphragm displacement may be transmitted by mechanical means to some form of indicators



For engineering measurements, diaphragm motion is sensed by some form of electrical secondary transducer



Resistive, capacitive, inductive, or piezoelectric



Natural frequency of the diaphragm should be sufficiently high to provide satisfactory frequency response



Output should be linear



# Flat Metal Diaphragm

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Deflection of flat metal diaphragm is limited either by stress requirements or deviation from linearity



As a general rule the maximum deflection that can be tolerated maintaining a linear pressure-displacement relation is about 30% of the diaphragm thickness

# Secondary Transducers Used with Diaphragms



Resistance strain gages with flat diaphragms

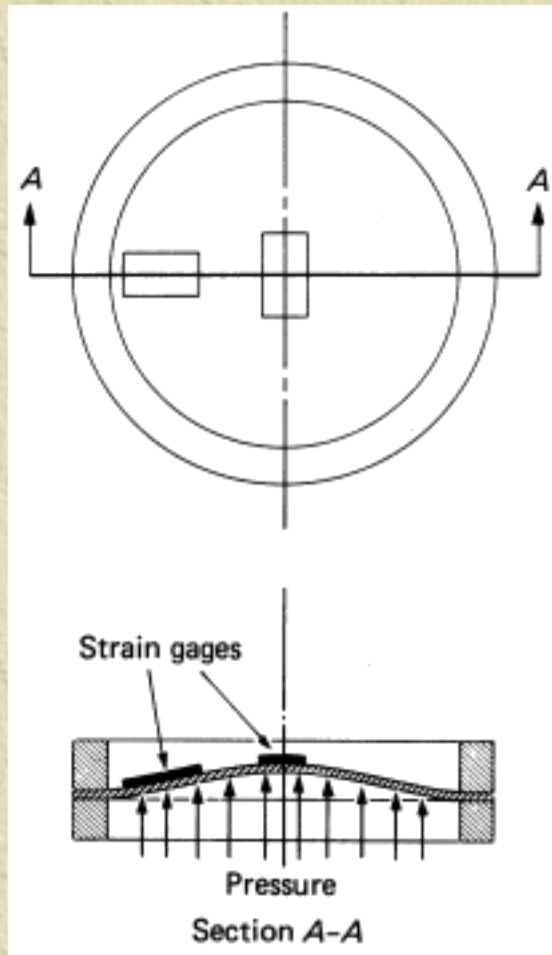


Inductive types 

Piezoelectric-type pressure cells



# Resistance Strain Gages



Location of strain gages on flat diaphragm

The central gage is subjected to tension while the outer gage senses compression



Apply strain gage directly to a diaphragm surface and calibrate the measured strain in terms of pressure

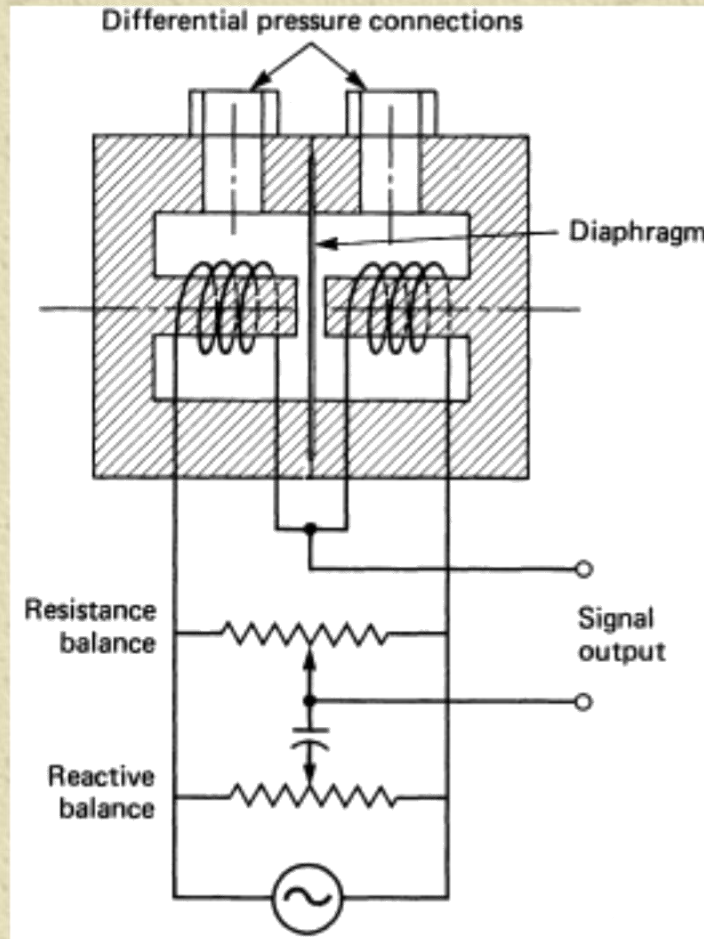


Drawback – the small physical area available for mounting the gages





# Inductive Types



Differential pressure cell with inductance-type secondary transducer



Flexing the diaphragm due to applied pressure causes it to move toward on pole piece and away from the other ↗



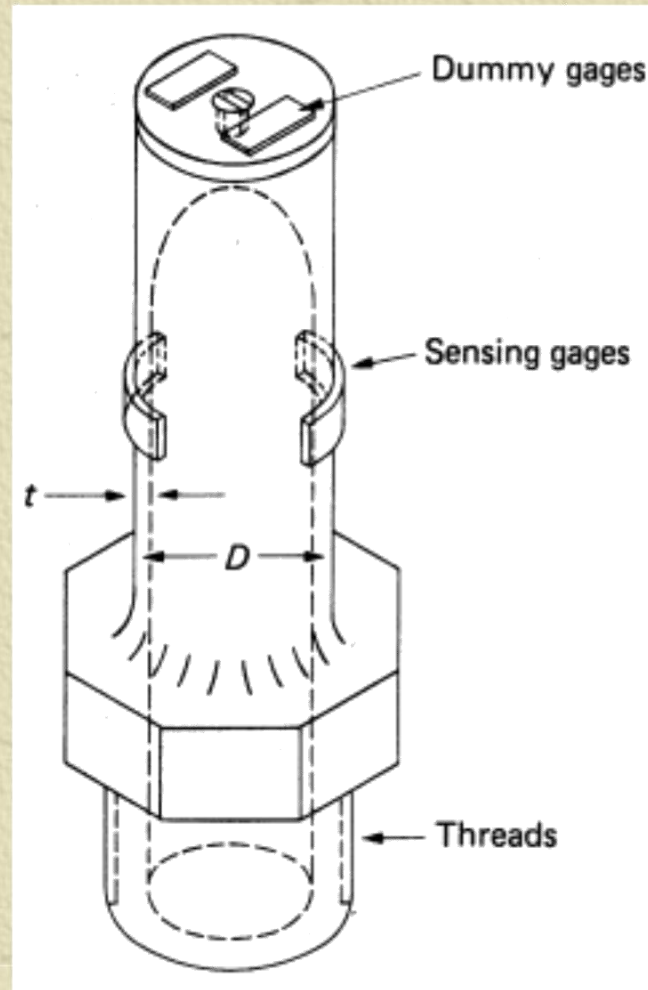
Altering the relative inductances



Standard laboratory equipment, such as an oscilloscope or electronic voltmeter, as well as recorders, may be used to display the gage output



# Cylindrical-Type Pressure Cell





# Measurement of Motion



Displacement



Velocity



Acceleration



Jerk

# Human Touch



In spite of the tremendous advances made in vibration-measuring instrumentation, one of the most sensitive vibration detectors is the human touch



Fingertips – sinusoidal vibrations having amplitudes as low as  $12 \mu$  in

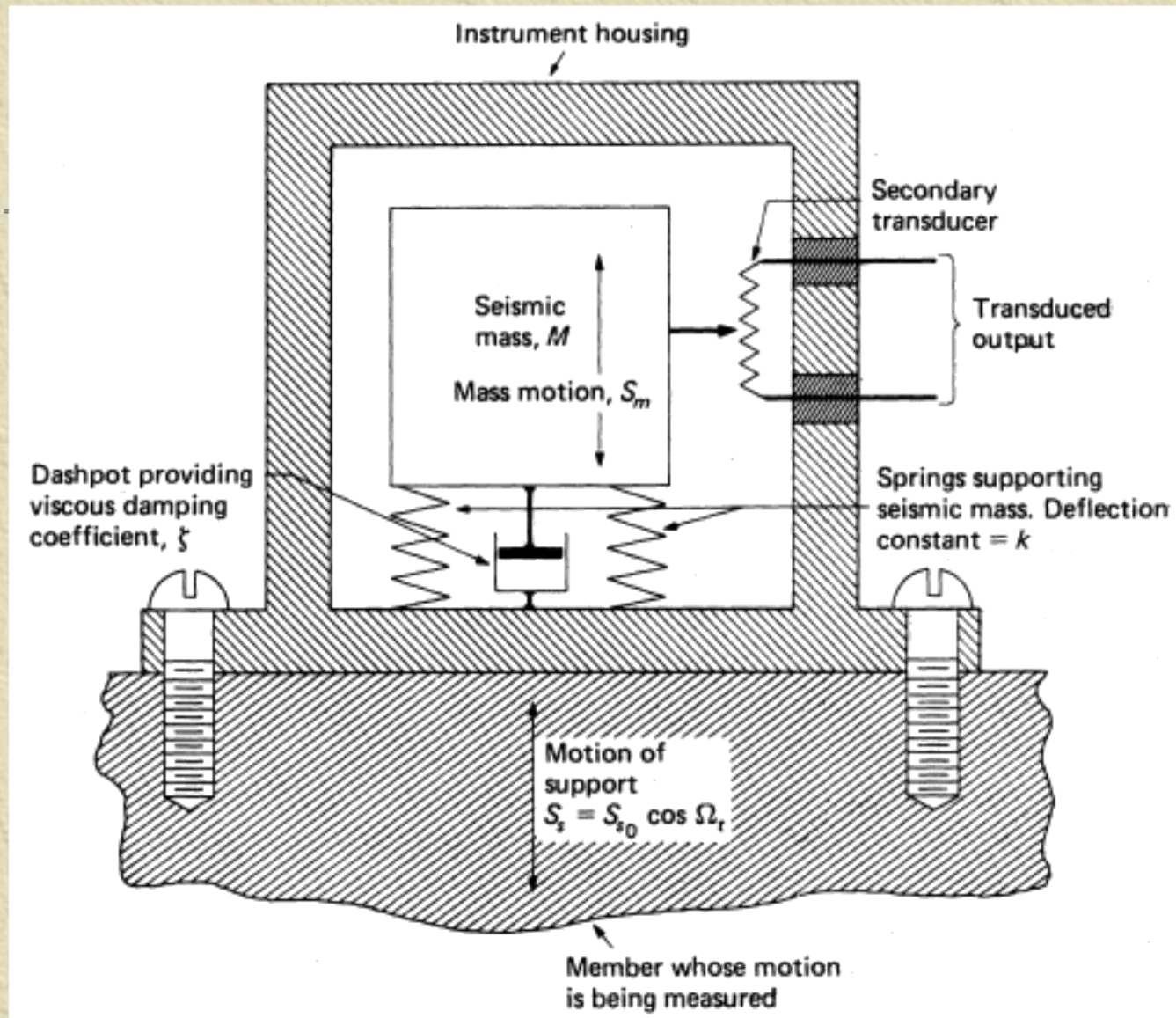


Vibrating member tightly gripped – average minimum detectable amplitude was only slightly greater than  $1 \mu$  in



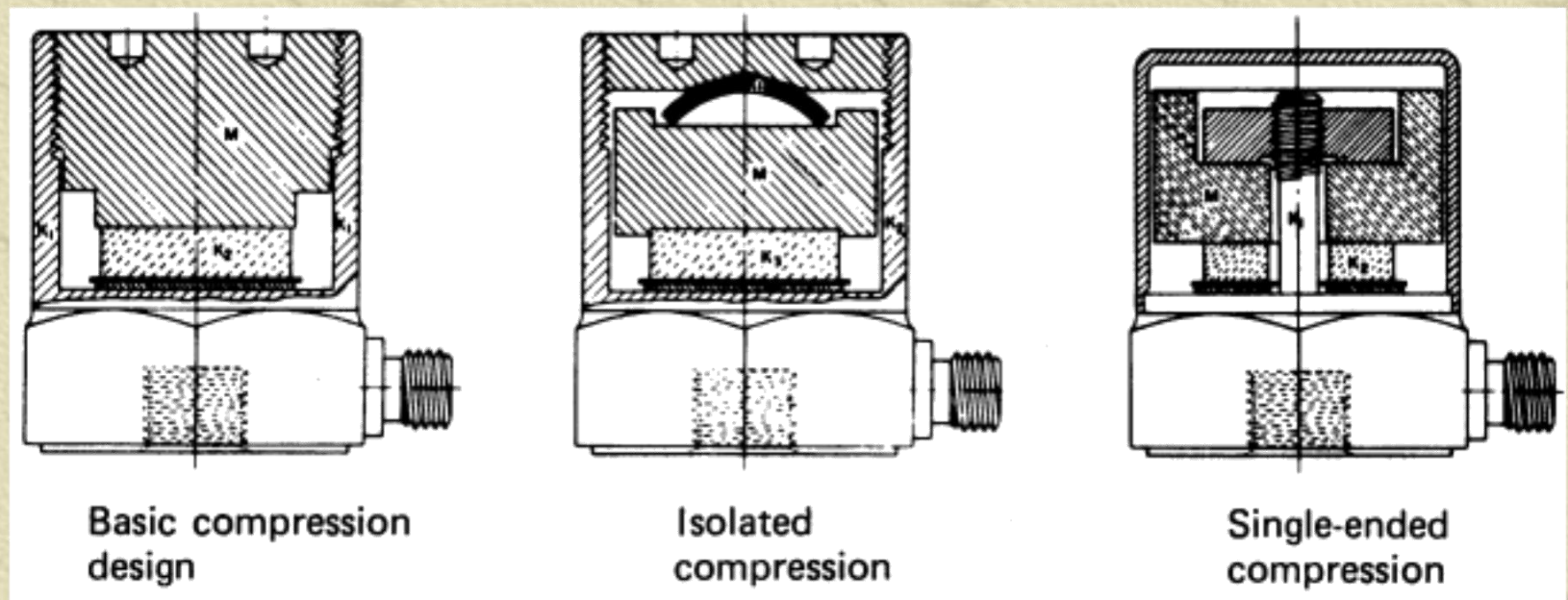
Greatest sensitivity occurred at a frequency of about 300 Hz





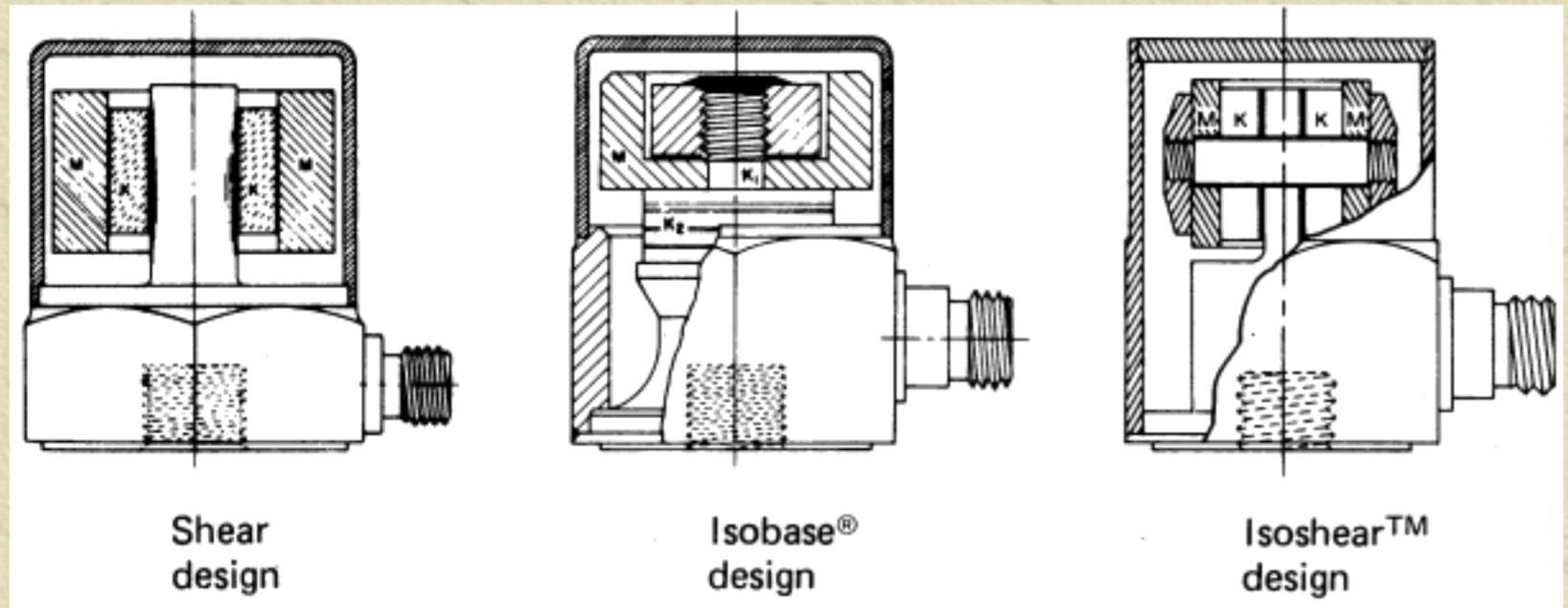
Seismic type of motion-measuring instrument





Typical piezoelectric-type accelerometer designs





# Advantages of Piezoelectric-Type Accelerometers



High sensitivity



Extreme compactness



Ruggedness

### Introduction to Humidity or dampness:

The amount of water vapour contained in air or gas is called humidity. It plays a vital role in many industrial processes such as chemical, textile, paper, food, leather, pharmaceutical Industries as Well as precision equipment manufacturing.

### Importance of humidity control:

13. Humidity should be measured and controlled to prevent the food products to become dry, spoilage of dried milk, eggs and for successful storage of fruits, meat etc.
14. Humidity should be controlled in order to reduce the affects of surface leakage in electrical installations.
15. It should be controlled to maintain proper environment conditions for human comforts.
16. Textile and paper industries require high humidity conditions. Any variations in humidity may cause the nature, behavior, characteristics of paper pulp and synthetic fibers to change.
17. It should be maintained and controlled in the required levels for proper drying process. If the humidity increases beyond the desired level (upper limit) the dry process may get retarded.

If it decreases below the lower limit the surface of the material becomes over dry.

Hence, the humidity is a very important process variable that should be controlled within the desired limits.

“Before going into the details of measuring of humidity it is important to known some terms related to humidity measurement”.

### Terminology:

14. **Humidity:** The amount of Water vapour contained in air or gas is called humidity.
15. **Dry Air:** When there is no Water vapour contained in the atmosphere, it is called dry air.
16. **Moist Air:** When their is water vapour contained in the atmosphere, then the air is called moist air.
17. **Saturated Air:** Saturated air is the moist air where the partial pressure of water - vapour equals the saturation pressure of steam corresponding to the temperature of air.
18. **Humidity Ratio or Specific Humidity or Absolute Humidity or Moisture Content:** It is defined as the ratio of the mass of water vapour to the mass of dry air in a given volume of the mixture and is denoted by  $w$

Humidity ratio =  $\frac{\text{mass of water vapour}}{\text{mass of dry air}}$



**xiii. Relative Humidity:** It is defined as the ratio of the mass of water vapour in a certain volume of moist

air at a given temperature to the mass of water vapour in the same volume of saturated air at the same temperature and is denoted by RH or  $\phi$ .

$$\text{Relative humidity} = \frac{\text{(Water vapour actually present)}}{\text{(Water vapour required for saturation)}} \quad (\text{At a given temperature})$$

Here a comparison is made between the humidity of air and the humidity of saturated air at the same temperature and pressure. It is to be noted that if relative humidity is 100 % it is saturated air, i.e., the air contains all the moisture it can hold.

It should also be noted that the degree of saturation (percentage of relative humidity) of air keeps on changing with temperature.

**j) Dew Point Temperature:** By continuous cooling at constant pressure if the temperature of air is reduced, the water - vapour in the air will start to condense at; particular temperature. The temperature at which the water vapour starts condensing is called as dew point temperature.

**k) Dry Bulb Temperature:** When a thermometer bulb is directly exposed to an air -water vapour mixture, the temperature indicated by the thermometer is the dry -bulb temperature.

This dry- bulb temperate is not affected by the moisture present in the air i.e. the temperature of air is measured in a normal way by the thermometer.

**12. Wet Bulb Temperature:** When a thermometer bulb is covered by a wet wick, and if the bulb covered by the wet wick is exposed to air, water vapour mixture, the temperature indicated by the thermometer is the wet bulb temperature. When air passed on the wet wick present on the bulb of the thermometer, the moisture present in the wick starts evaporating and this creates a cooling effect at the bulb. The bulb now measures the thermodynamic equilibrium temperature reached between then cooling affected by the evaporation of water and heating by convection.

**13. Wet - Bulb Depression:** Wet - bulb depression = (Dry - bulb temperature) - (Wet bulb temperature)

Always dry - bulb temperature is higher than the wet bulb temperature.

i.e., (Dry - bulb temperature > Wet bulb temperature)

**14. Percentage Humidity:** It is defined as ratio of weight of water vapour in a unit weight of air to weight of water vapour in the same weight of air if the air were completely saturated at the same temperature.

$$\text{Percentage humidity} = \frac{\text{(Weight of water vapour in a unit weight of air)}}{\text{(Weight of water vapour in the same weight of air if the air were completely saturated at the same temperature.)}}$$

#### **LIST OF INSTRUMENTS USED TO MEASURE HUMIDITY:**

The three main instruments used for measuring humidity are....

13) Sling psychrometer

14) Absorption hygrometer.

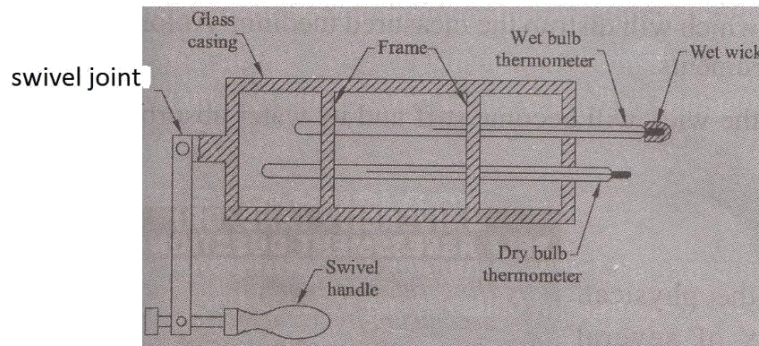
(a) Mechanical humidity sensing absorption hygrometer.



13)Electrical humidity sensing absorption hygrometer.

3. Dew point meter.

### **1. Sling psychrometer:-**



**Principle:** This instrument is used to measure both the dry bulb and wet bulb temperatures at a time with these temperatures we can measure the humidity content in air.

**Description:** The main parts of the instrument are

A frame holding two thermometers to measure dry & wet bulb temperatures as shown fig. Two mercury in glass thermometers, one to measure dry - bulb temperatures and the other to measure Wet-bulb temperature.

The frame carrying the thermometers is covered by a glass casing. A swivel handle is attached to the frame - glass casing - thermometer arrangement to ensure that the air at the wet bulb is always in immediate contact with the wet wick.

**Operation:** Accurate measurement of wet bulb temperature is obtained only if air moves with a velocity around the wet wick.

In order to measure wet bulb temperature, the psychrometer frame & glass covering thermometer arrangement is rotated at 5 m/ s to 10 m/ s to get the necessary air motion. The thermometer whose bulb is bare (Without wick) contacts the air and indicates the dry bulb temperature. At the same time, the thermometer whose bulb is covered with the wet wick comes in contact with the air and when this air passes on the wet Wick, the moisture present in the wick starts evaporating and a cooling effect is produced at the bulb. This temperature is the wet bulb temperature, which will be naturally less than the dry bulb temperature.

### **Applications:**

☐ It is used for checking humidity level in air conditioned rooms and installations.

☐ This is used for setting & checking hair hygrometers.

☐ It is used in the measurement range of 0 to 100 % RH and can measure Wet bulb temperatures between 0° C to 180° C.

- It is used for measuring wet bulb temperatures between 0° C to 180° C.

**Limitations:**

- 24) Continuous recording of humidity is not possible. The evaporation process at the wet bulb will add moisture to the air, which will disturb the measured medium. Automation is not possible with this instrument.
- 25) If the wick is covered with dirt, the wick will become stiff and its water absorbing capacity will reduce.

**2. Absorption hygrometer:**

Principle: Humidity changes the physical, chemical and electrical properties of several materials. This property is used in transducers that are designed and calibrated to read relative humidity directly.

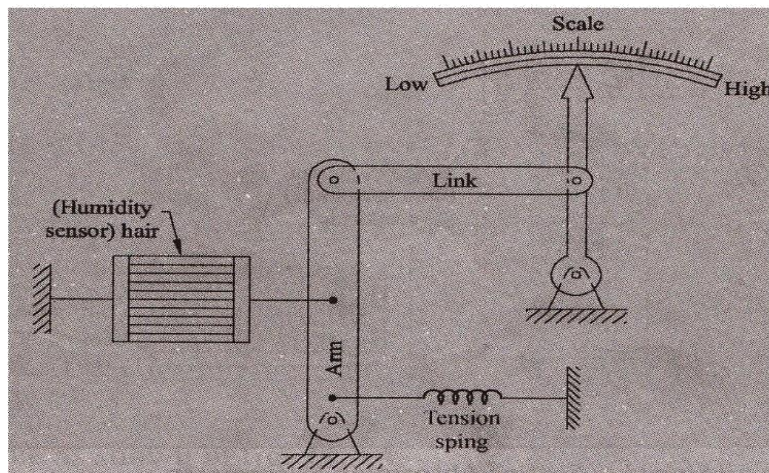
There are two types of absorption hygrometers namely;

- (a). Mechanical humidity sensing absorption hygrometer.
- (b). Electrical humidity sensing absorption hygrometer.

**Mechanical Humidity Sensing Absorption Hygrometer:**

**Principle:**

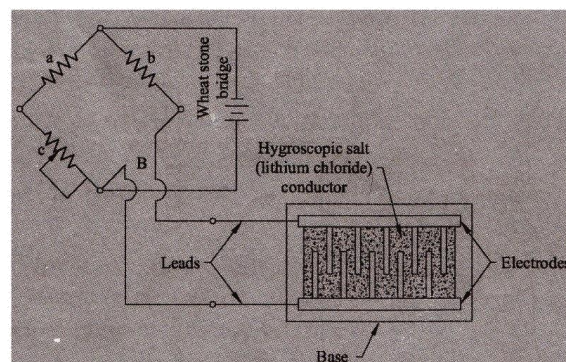
Hygroscopic materials such as human hair, animal membranes, Wood, paper etc, undergo changes in linear dimensions when they absorb moisture from their surrounding air. This change in linear dimension is used for the measurement of humidity present in air. A hair hygrometer has been shown in fig.



**Description:**

The main parts of the mechanical hair hygrometer type are:

- s) Human hair as the humidity sensor. The hair is arranged in parallel beam and they are separated from one another to expose them to the surrounding air. Number of hairs are placed in parallel to increase mechanical strength as shown in fig.



**Operation:**

The electrodes coated with lithium chloride are exposed to atmosphere, whose humidity is to be measured.

Humidity variation causes the resistance of lithium chloride to change. i.e., the chemical absorbs or loses moisture and causes a change in resistance.

Higher the humidity ( RH) in the atmosphere, more will be the humidity absorbed by lithium chloride and lower will be the resistance and higher will be the resistance in case of lesser humidity.

The change in resistance is measured using a Wheatstone bridge which becomes a measure of humidity (RH) present in the atmosphere.

**Applications:**

-These are used under constant temperature conditions.

-The accuracy of this instrument is  $\pm 25\%$

-The response is very fast, of the order of few seconds.

**Limitations:**

This instrument should not be exposed to 100 % humidity as this makes chemical absorb all the humidity and damage the instrument.

Temperature corrections must be made if they are not used at constant temperature conditions.

**3. Dew point meter:-**

**Principle:** At constant pressure if the temperature of air is reduced, the water vapour in the will start to condense at a particular temperature. This temperature is called dew point temperature.

**Description:**

The main parts of the arrangement are:

F) A shiny mirror surface fixed with a thermocouple as shown in fig.

G) A nozzle to provide a jet of air on the mirror.

H) A light source focused constantly on the mirror.

I) A photo cell to detect the amount of light reflected from the mirror.

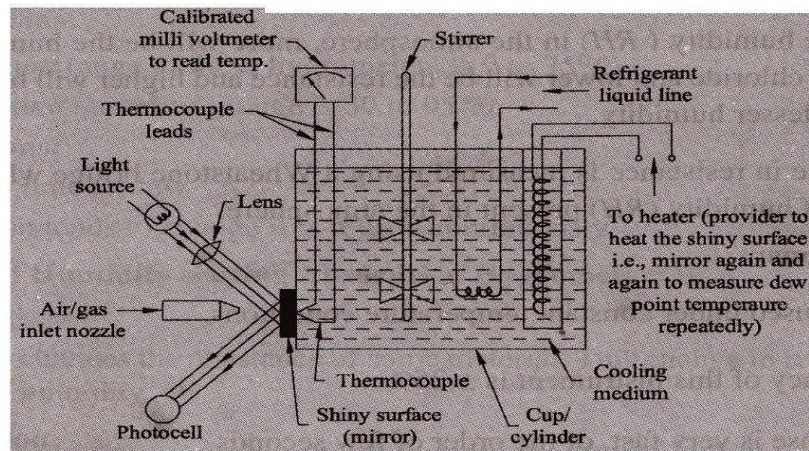
**Operation:**

-The mirror is constantly cooled by a cooling medium, which is maintained at a constant temperature.

-A thermocouple is attached to this mirror, whose leads are connected, to a milli voltmeter.

-Constantly a light is made to fall at an angle on the mirror and the amount of reflected light is sensed by a photo cell as shown in fig.





-Now an air jet is made to fall on the mirror and the water- vapour (moisture) contained in the air starts condensing on the mirror and they appear as small drops (dews) on the mirror.

-This moisture formed on the mirror reduces the amount of light reflected, which is detected by the photocell. When for the first time, there is a change in the amount of transmitted light, it becomes an indication of dew formation. At this instance i.e., the temperature indicated by the thermocouple attached to the mirror becomes the dew-point temperature.

-This instrument is used to know the time at which the dew appears for the first time and to know the dew point temperature.

#### **Applications:**

-Cargoes can be protected from condensation damage by this instrument by maintaining the dew point of air in holds lower than the cargo temperature.

-Used in industries for determining dew point.

#### **Limitations:**

-Effective light measurement is not possible.

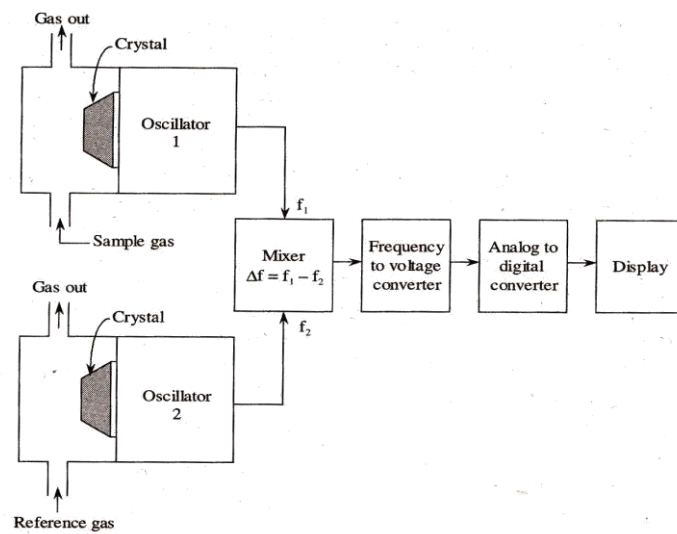
-Limitations is cooling fluids exists.

#### **Explain one method of measurement of moisture content of gases:**

A hygrometer based on the quartz crystal oscillator is used to measure the moisture content of gases such as ethylene, hydrogen, refrigerants and natural gas.

When a quartz crystal coated with a layer of hygroscopic materials (the materials which exhibit a change in their dimensions when they absorb moisture) is subjected to gas sample, the weight of the crystal increases as the hygroscopic materials absorb the moisture. As the 'weight of the crystal increases, its frequency changes. An oscillator employing quartz crystal coated with hygroscopic material and used for the measurement of humidity (or moisture) is shown in figure given below,

In the above arrangement, two crystals are used. The two crystals are alternately subjected to two different gases for a period of about 30 seconds, so that their contaminations become same and a stable frequency output is obtained.



The frequency shifts of the crystal due to the change of its weight in the presence of moisture of sample gas are measured electronically and the difference in frequency is determined. This frequency difference is converted into signal, which is then converted into digital form and displayed. Thus, quartz crystal hygrometer can measure humidity or moisture content of gases ranging from 1Vppm to 30Vppm.

# UNIT-V

## MEASUREMENT OF FORCE, TORQUE AND POWER

An engineer is concerned not only with the generation of power by a prime-mover but is also required to measure the useful output. That helps the engineer to know how well prime-mover is doing its job in relation to the energy supplied to it. The terms related to engine output are:

**xiii) Force:** Force represents the mechanical quantity which changes or tends to change the relative motion or shape of the body on which it acts. Force is vector quantity specified completely by its magnitude, point of application, line of action and direction.

The relationship between motion and force is provided by the laws of dynamics. Newton's second law of motion states that force is proportional to the rate of change of momentum. That is

$$\text{force} \propto \text{rate of change of momentum}$$

Momentum is the product of mass and velocity of a body and represents the energy of motion stored in a moving body

$$\therefore \text{force} \propto \text{rate of change of (mass} \times \text{velocity)}$$

$$\propto \text{mass} \times \text{rate of change of velocity}$$

$$\propto \text{mass} \times \text{acceleration}$$

$$\text{Thus } F \propto ma : F = \frac{ma}{g_c}$$

where  $m$  is the mass,  $a$  is acceleration and  $g_c$  is proportionality constant.

The SI unit of force is newton (N) which represents the force required to accelerate 1 kg mass with an acceleration of 1 m/s<sup>2</sup>

$$\text{Thus } 1\text{N} = \frac{1\text{ kg} \times 1\text{ m/s}^2}{g_c} \text{ and } g_c = \frac{1\text{ kg m}}{\text{N s}^2}$$

The constant of proportionality becomes unity for defining unit of force as

newton and accordingly is dropped. Such a practice corresponds to writing Newton's law as

$$\text{Force} = \text{mass} \times \text{acceleration} ; F = ma$$

$$\therefore 1\text{N} = 1 \frac{\text{kg m}}{\text{s}^2}$$

Force is also measured in gravitational units expressed as kilogram force ( $\text{kg}_f$ ). A  $\text{kg}_f$  is defined as that force which when applied to a body of 1 kg mass produces an acceleration equal to  $9.81 \text{ m/s}^2$  (gravitational acceleration near the earth's surface)

$$1 \text{ kg}_f = 1 \text{ kg} \times 9.81 \text{ m/s}^2 = 9.81 \text{ kg m/s}^2$$

The newton and kilogram force are connected by the relation

$$1 \text{ kg}_f = 9.81 \text{ N}$$

**11) Work:** Work represents the product of force and the displacement measured in the direction of force.

Work done = force  $\times$  displacement;

$$W = F s$$

The unit of work is joule (J) which is defined as the work done by a constant force of one newton acting on a body and moving it through a distance of one metre in its direction.

$$1 \text{ J} = 1 \text{ N m}$$

**11. Torque:** It represents the amount of twisting effort, and numerically it equals the product of force and the moment arm or the perpendicular distance from the point of rotation (fulcrum) to the point of application of force. Consider a wheel rotated by the force  $F$  applied at radius  $r$ . Torque or twisting moment is then given by

$$T = F \times r$$

Thus measurement of torque is intimately related to force measurement.

**g) Power:** Power is the rate of doing work and is obtained by dividing the work done by time. The unit of power is watt (W), kilowatt (kW) or megawatt (MW). Watt represents a work equivalent of one joule done per second.

$$\text{Power} = \text{work done per unit time}$$

$$\text{Thus } 1 \text{ W} = 1 \text{ J/s} = \text{Nm/s}$$

$$1 \text{ kW} = 10^3 \text{ W} \text{ and } 1 \text{ MW} = 10^6 \text{ W}$$

With reference to Fig. 13.1, the work done by the wheel from A to B is

$$= \text{force} \times \text{distance moved}$$

$$= \text{force} \times \text{length of arc AB}$$

$$= \text{force} \times r \theta = (F \times r) \theta = T \theta$$

Thus the work done by torque is given by the product of torque and the angular displacement.

In one rotation  $= 2\pi$ . If the wheel thus  $N$  revolutions per minute, then the angular displacement per second is  $2\pi N / 60$ .

$$\text{work done} = T \times \frac{2\pi N}{60} \text{ Nm/s}$$

$$\text{Power} = \frac{2\pi NT}{60} \text{ watt}$$

In many mechanical applications, power is still quoted in unit of horse power (HP) which equals the work done at the rate of  $75 \text{ m kg}_f/\text{s}$ . This power unit is related to watt (W) and kilowatt (kW) by the relation.

$$1 \text{ HP} = 736 \text{ W} = 0.736 \text{ kW}$$



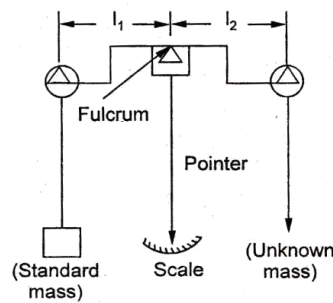
### Force Measurement:

A measure of the unknown force may be accomplished by the methods incorporating following principles:-

- u) Balancing the force against a known gravitational force on a standard mass (scales balances)
- v) Translating the force to a fluid pressure and then measuring the resulting pressure and pneumatic load cells)
- w) Applying the force to some elastic member and then measuring the resulting (proving ring)
- x) Applying the force to a known mass and then measuring the resulting acceleration
- y) Balancing the force against a magnetic force developed by interaction of a magnet current carrying coil.

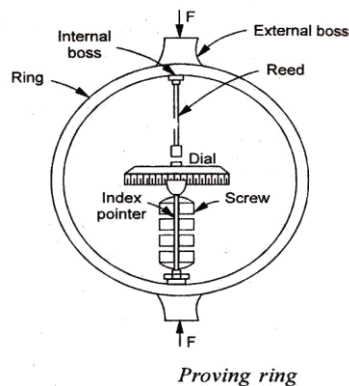
### Scales and balances:

Force or weight is indicated by making a comparison the force due to gravity acting on a standard mass and the force due to gravity on the unknown mass.



An equal-arm beam balance of a beam pivoted on a knife-edge fulcrum the centre. Attached to the centre of the beam a pointer which points vertically downwards the beam is in equilibrium. The equilibrium exist when the clockwise rotating equals the anti-clockwise rotating moment i.e.,  $1 \neq 2$ . Since the two arms of the beam equal; the beam would be in equilibrium again  $1 = 2$ . Further for a given location, the attraction acts equally on both the masses therefore at the equilibrium conditions  $1 = 2$ , i. e., the unknown force or weights equal known force or weights.

### PROVING (STRESS) RING:

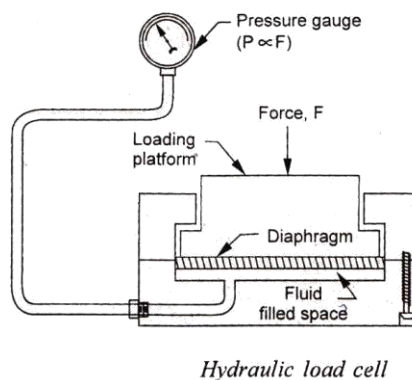


The proving (stress) ring is a ring of known physical dimensions and mechanical properties. When an external compressive or tensile load is applied to the lugs or external bosses, the ring changes in its diameter; the change being proportional to the applied force. The amount of ring deflection is measured by means of a micrometer screw and a vibrating reed which are attached to the internal bosses. During use, the micrometer tip is advanced and its contact with the reed is indicated by considerable damping of the reed vibration. The difference in the micrometer reading taken before and after the application of load is the measure of the amount of the elongation or compression of the ring. The proving ring deflection can also be picked by LVDT, resulting in a proportional voltage change. The device gives precise results when properly calibrated and corrected for temperature variations.

Instead of deflection, strain in an elastic member may be measured by a strain gauge, and then correlated to the applied force.

**Mechanical load cells:** The term load cell is used to describe a variety of force transducers which may utilize the deflection or strain of elastic member, or the increase in pressure of enclosed fluids. The resulting fluid pressure is transmitted to some form of pressure sensing device such as a manometer or a bourdon tube pressure gauge. The gauge reading is identified and calibrated in units of force.

#### **Hydraulic load cell:**

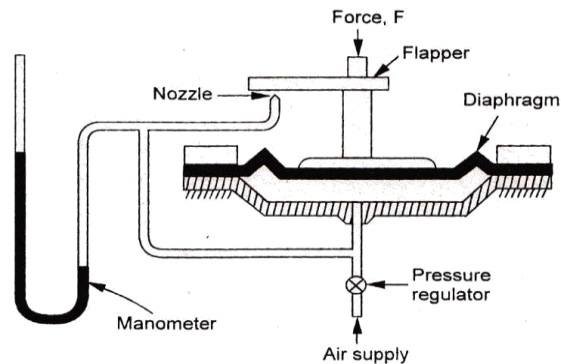


In a hydraulic load cell the force variable is impressed upon a diaphragm which deflects and there by transmits the force to a liquid. The liquid medium, contained in a confined space, has a preload pressure of the order of 2 bar. Application of force increases the liquid pressure; it equals the force magnitude divided by the effective area of the diaphragm. The pressure is transmitted to and read on an accurate pressure gauge calibrated directly in force units. The system has a good dynamic response; the diaphragm deflection being less than 0.05 mm under full load. This is because the diaphragm has a low modulus and substantially all the force is transmitted to the liquid. These cells have been to measure loads up to about 2.5 MN with an accuracy of the order of 0.1 percent of full scale; resolution is about 0.02 percent.

#### **pneumatic load cell:**

A pneumatic load cell operates on the force-balance principle and employs a nozzle-flapper transducer similar to the conventional relay system. A variable downward force is balanced by an upward force of air pressure against the effective area of a diaphragm. Application of force causes the flapper to come closer to the nozzle, and the diaphragm to deflect downwards. The nozzle opening is nearly shut-off and

this results into an increased back pressure in the system. The increased pressure acts on the diaphragm, produces an effective upward force which tends to return the diaphragm to its preload position.

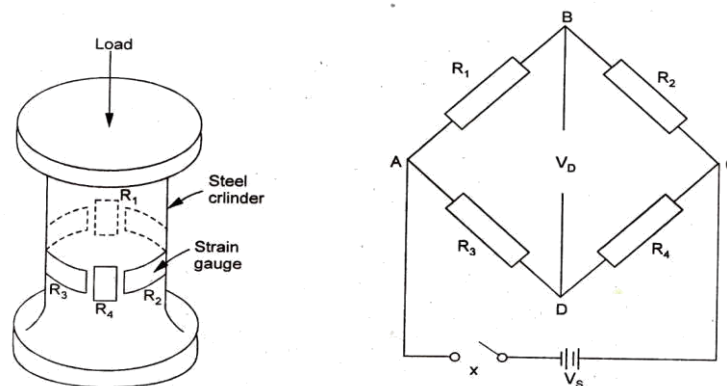


*Pneumatic load cell*

For any constant applied force, the system attains equilibrium at a specific nozzle opening and a corresponding pressure is indicated by the height of mercury column in a manometer. Since the maximum pressure in the system is limited to the air-supply pressure, the range of 'M unit can be extended only by using a larger diameter diaphragm. The commercially available load cells operating on this principle can measure loads up to 250 kN with an accuracy of 0.5 percent of full scale. The air consumption is of the order of  $0.17 \text{ }^3/\text{hr}$  of free air.

### Strain gauge load cell:

The strain gauge load cell converts weight or force into electrical outputs which are provided by the strain gauges; these outputs can be connected to various measuring instruments for indicating, recording and controlling the weight or force.



A simple load cell consists of a steel cylinder which has four identical strain gauges mounted upon it; the gauges 1 and 4 are along the direction of applied load and the gauges 2 and 3 are attached circumferentially at right angles to gauges 1 and 4. These four gauges are connected electrically to the four limbs of a Wheatstone bridge circuit. When there is no load on the cell, all the four gauges have the same resistance. Evidently then the terminals B and D are at the same potential; the bridge is balanced and the output voltage is zero.

$$V_{ab} = V_{ad} = \frac{V_s}{2}$$

$$V_0 = V_{ab} - V_{ad} = 0$$

When a compressive load is applied to the unit, the vertical gauges ( $R_1$  and  $R_4$ ) undergo compression and so decrease in resistance. Simultaneously the circumferential gauges  $R_2$  and  $R_3$  undergo tension and so increase in resistance. In the Poisson's arrangement, the positive and negative strains (and so changes in resistance) are related to each other by the Poisson's ratio. Thus when strained, the resistance of the various gauges are :

$$R_1 \text{ and } R_4 = R - dR \quad (\text{compression})$$

$$R_2 \text{ and } R_3 = R + \mu dR \quad (\text{tension})$$

Potential at terminal B is,

$$\begin{aligned} V_{ab} &= \frac{R_1}{R_1 + R_2} V_s \\ &= \frac{R - dR}{(R - dR) + (R + \mu dR)} V_s = \frac{R - \mu dR}{2 R - dR (1 - \mu)} V_s \end{aligned}$$

Potential at terminal D is,

$$\begin{aligned} V_{ad} &= \frac{R_3}{R_3 + R_4} V_s \\ &= \frac{R + \mu dR}{(R + \mu dR) + (R - dR)} V_s = \frac{R + \mu dR}{2 R - dR (1 - \mu)} V_s \end{aligned}$$

The changed output voltage is,

$$\begin{aligned} V_0 + dV_0 &= \frac{R - dR}{2 R - dR (1 - \mu)} V_s = \frac{R + \mu dR}{2 R - dR (1 - \mu)} V_s \\ &= \frac{dR (1 + \mu)}{2R} V_s = 2 (1 + \mu) \left( \frac{dR}{R} \frac{V_s}{4} \right) \end{aligned}$$

The output voltage  $V_0 = 0$  under unloaded conditions, and therefore change in output voltage due to applied load becomes.

$$dV_0 = 2 (1 + \mu) \left( \frac{dR}{R} \frac{V_s}{4} \right) \quad \dots(13.14)$$

Apparently this output voltage is a measure of the applied load. The use of four identical strain gauges each arm of the bridge provides full temperature compensation and also increases the bridge sensitivity  $2 (1 + \mu)$  times.

The strain gauge load cells are excellent force measuring devices, particularly when the force is not steady. They are generally stable, accurate and find extensive use in industrial

applications such as draw-bar and tool-force dynamometers, crane load monitoring, and road vehicle weighing device etc.



**Problem:**

A strain gauge load cell consists of a solid steel cylinder which has 4-identical strain gauges mounted upon it in the Poisson's arrangement (Fig. 13.10). For each gauge the nominal resistance  $R = 100 \Omega$ , gauge factor  $F = 2.0$  and the gauges are connected electrically to the four arms of a wheatstone bridge circuit which is energised with a supply voltage of 6 volts. Make calculations for the sensitivity of the load cell. The steel cylinder is 50 mm in diameter and for steel the modulus of elasticity  $E = 200 \text{ GN/m}^2$  and the Poisson's ratio  $\mu = 0.3$ .

**Solution :** Consider a load of 1 kN applied to the load cell.

$$\begin{aligned}\text{stress} &= \frac{\text{load}}{\text{cross-sectional area}} = \frac{1 \times 10^3}{\frac{\pi}{4} (50 \times 10^{-3})^2} \\ &= 0.5095 \times 10^6 \text{ N/m}^2 \\ \text{strain} &= \frac{\text{stress}}{\text{modulus of elasticity}} = \frac{0.5095 \times 10^6}{200 \times 10^9} \\ &= 2.5475 \times 10^{-6}\end{aligned}$$

Fractional change in resistance,

$$\begin{aligned}\frac{dR}{R} &= F \epsilon = 2.0 \times 2.5475 \times 10^{-6} \\ &= 5.095 \times 10^{-6}\end{aligned}$$

$$\begin{aligned}\text{Output voltage } dV_o &= 2 (1 + \mu) \left( \frac{dR}{R} \frac{V_s}{4} \right) \\ &= 2 (1 + 0.3) \left( 5.095 \times 10^{-6} \times \frac{6}{4} \right) \\ &= 19.87 \times 10^{-6} = 19.87 \mu\text{V}\end{aligned}$$

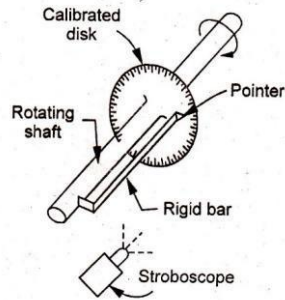
Hence the gauge sensitivity is  $19.87 \mu\text{V/kN}$

**Torques measurement:**

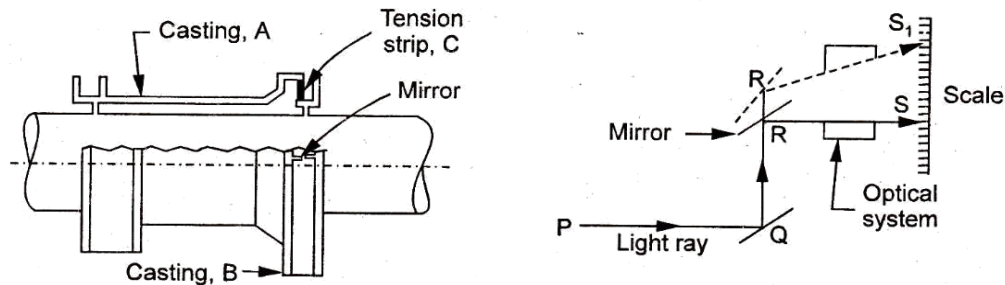
The main purpose of torque measurement is to determine the mechanical power required or developed by a machine. Torque measurement also helps in obtaining load information necessary for stress or strain analysis. In some cases other variables are determined by measuring torque. For example, in the case of rotating cylinder viscometer, measurement of torque developed at the fixed end of the stationary cylinder help in determining the viscosity of the fluid between the movable and stationary cylinder.

**Mechanical torsion meter:**

Figure shows the schematics of an elastic torsion bar meter wherein angular deflection of a parallel length of shaft is used to measure torque. The angular twist over fixed length of the bar is observed on a calibrated disk (attached to the rotating shaft) by using the stroboscope effect of intermittent viewing and the persistence of vision. The system gives a varying angle of twist between the driving engine and the driven load as the torque changes.



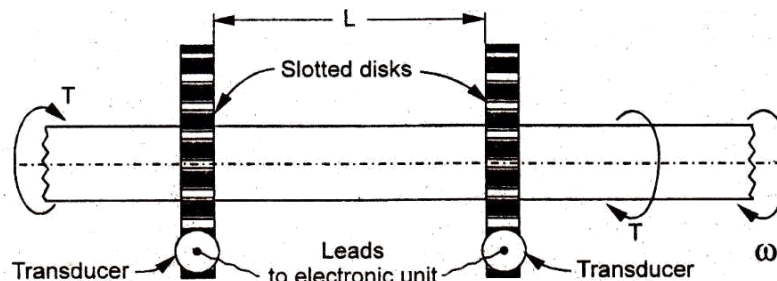
**Optical torsion meter:** The meter uses an optical method to detect the angular twist of a rotating shaft.



The unit comprises two castings A and B which are fitted to the shaft at a known distance apart. These castings are attached to each other by a tension strip C which transmits torsion but has little resistance to bending. When the shaft is transmitting a torque, there occurs a relative movement between the castings which results in partial inclination between the two mirrors attached to the castings. The mirrors are made to reflect a light beam onto a graduated scale; angular deflection of the light ray is then proportional to the twist of, and hence the torque in, the shaft. For constant torque measurements from a steam turbine, the two mirrors are arranged back to back and there occurs a reflection from each mirror during every half revolution. A second system of mirrors giving four reflections per revolution is desirable when used with a reciprocating engine whose torque varies during a revolution.

**Electrical torsion meter:** A system using two magnetic or photoelectric transducers, as shown in Fig, involves two sets of measurements.

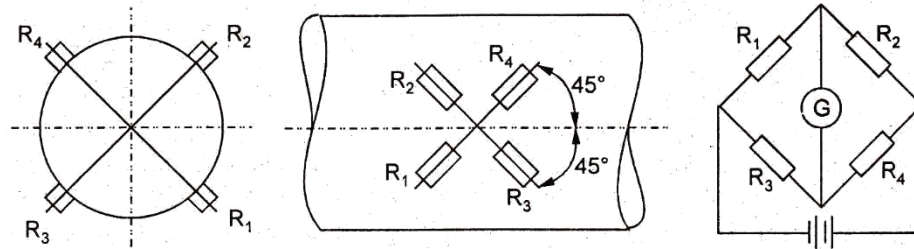
(i) a count of the impulse from either slotted wheel. This count gives the frequency or shaft speed.



(xi) a measure of the time between pulses from the two wheels. This signal is proportional to the twist of, and hence torque T in the shaft.

These two signals,  $T$  and  $\omega$ , can be combined to estimate the power being transmitted by the shaft.

**Strain- gauge torsion meter:** A general configuration of a strain gauge bridge circuit widely employed for torque measurement from a rotating shaft is shown in Fig.



Four bonded-wire strain gauges are mounted on a  $45^\circ$  helix with the axis of the rotation and are placed in pairs diametrically opposite. If the gauges are accurately placed and have matched characteristics, the system is temperature compensated and insensitive to bending and thrust or pull effects. Any change in the gauge circuit then results only from torsional deflection. When the shaft is under torsion, gauges 1 and 4 will elongate as a result of the tensile component of a pure shear stress on one diagonal axis, while gauges 2 and 3 will contract owing to compressive component on the other diagonal axis. These tensile and compressive principal strains can be measured, and the shaft torque can be calculated.

A main problem of the system is carrying connections from the strain gauges (mounted on the rotating shaft) to a bridge circuit which is stationary. For slow shaft rotations, the connecting wires are simply wrapped around the shaft. For continuous and fast shaft rotations, leads from the four junctions of the gauges are led along the shaft to the slip rings. Contact with the slip rings is made with the brushes through which connections can be made to the measuring instrument.

Commercial-strain-gauge torque sensors are available with built-in slip rings and speed sensors. A family of such devices covers the range 6 Nm to 1000 kNm with full-scale output of about 40 mV.

### **SHAFT POWER MEASUREMENT (DYNAMOMETERS):-**

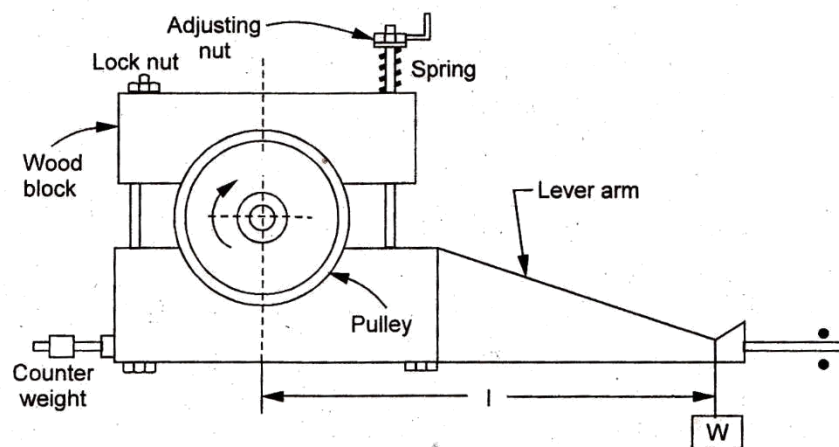
The dynamometer is a device used to measure the torque being exerted along a rotating shaft so as to determine the shaft power input or output of power-generating, transmitting, and absorbing machinery. Dynamometers are generally classified into:

**(j) Absorption dynamometers** in which the energy is converted into heat by friction whilst being measured. The heat is dissipated to the surroundings where it generally serves no useful purpose. Absorption dynamometers are used when the test-machine is a power generator such as an engine, turbine and an electric motor. The types commonly used include Prony brakes, hydraulic or fluid friction brakes, fan brakes and eddy current dynamometers.

**(k) Transmission dynamometers** in which the energy being transmitted either to or from dynamometer is not absorbed or dissipated. After measurement, the energy is conveyed to the surroundings in a useful mechanical or electrical form. A small amount of power may, however, be lost by friction at the joints of the dynamometer. The type includes torsion and belt dynamometers, and strain gauge dynamometers.

**g) Driving dynamometer** which may be coupled to either power-absorbing or power generating devices since it may operate either a motor or a generator. These instruments measure power and also supply energy to operate the tested devices. They are essentially useful in determining performance characteristics of such machines as pumps and compressors. Electric cradled dynamometer is a typical example of the driving dynamometer.

**Mechanical brakes:** The Prony and the rope brakes are the two types of mechanical brakes chiefly employed for power measurement. The prony brake has two common arrangements in the block type and the band type. Whereas the block type is employed to high speed shafts with a small pulley, the band type measures the power of low speed shafts having a relatively large pulley.



The block type prony brake consists of two blocks of wood each of which embraces rather less than one half of the pulley rim. One block carries a lever arm to the end of which a pull can be applied by means of a dead weight or spring balance. A second arm projects from the block in the opposite direction and carries a counter-weight to balance the brake when unloaded. When operating, friction between the blocks and the pulley tends to rotate the blocks in the direction of the rotation of the shaft. This tendency is prevented by adding weights at the extremity of the lever arm so that it remains horizontal in a position of equilibrium.

Let  $W$  be the weight in newton,  $l$  be the effective length of the lever arm in meter, and  $N$  be the revolutions of the crankshaft per minute. Then:

$$\text{Torque } T = W l \quad \text{in Nm}$$

and 
$$\text{Power } P = \frac{2\pi N}{60} \times T \quad \text{in Nm/s}$$

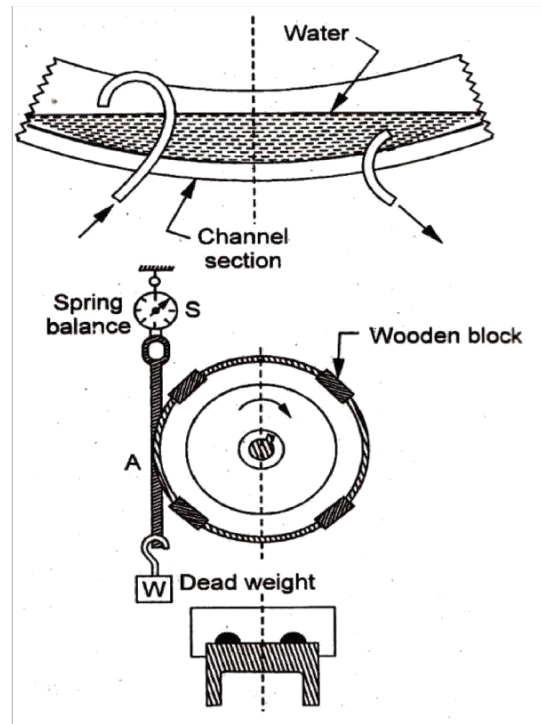
$$= \frac{2\pi N}{60 \times 1000} \times W l \quad \text{in kW}$$

It may be noted that the power absorbed by this type of dynamometer is independent of the size of the brake and the coefficient of friction.



### Rope brake dynamometers:

A rope brake dynamometer consists of one or more ropes wrapped around the fly wheel of an engine whose power is to be measured. The ropes are spaced evenly across the width of the rim by means of U-shaped wooden blocks located at different points of the rim of the flywheel. The upward ends of the rope are connected together and attached to a spring balance, and the downward ends are kept in place by a dead weight. The rotation of flywheel produces frictional force and the rope tightens. Consequently a force is induced in the spring balance. Generation of heat is enormous and that necessitates a cooling arrangement for the brake. The rim is made trough shaped internally. Water is run into the trough and kept in place by the centrifugal force.



Let  $W$  be the dead weight,  $S$  be the spring balance reading ;  $D$  be the brake drum diameter, and  $d$  be the rope diameter. Then effective radius of the brake drum  $R_{eff} = (D + d)/2$ .

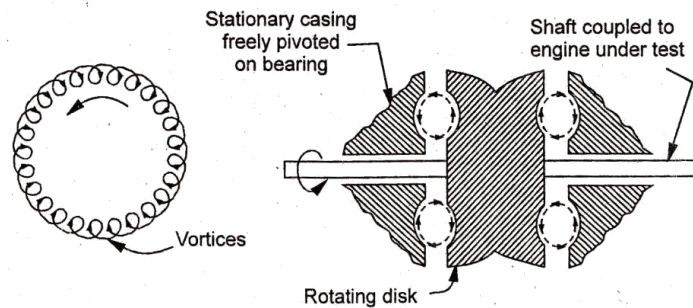
Brake load or net load =  $(W - S)$  in N

Braking torque =  $(W - S) R_{eff}$  in Nm

$$\text{Brake power} = \frac{2\pi N}{60} \times T \quad \text{in Nm/s}$$

$$= \frac{2\pi N}{60 \times 1000} \times (W - S) R_{eff} \quad \text{in kW}$$

## Hydraulic dynamometer:-



A hydraulic dynamometer uses fluid-friction rather than dry friction for dissipating the input energy. The unit consists essentially of two elements namely a rotating disk and stationary casing. The rotating disk is keyed to the driving shaft of the prime-mover and it revolves inside the stationary casing. The casing is mounted on antifriction (trunnion) bearings and has a brake arm and a balance system attached to it. Such bearings allow the casing to rotate freely except for the restraint imposed by the brake arm. Further, the casing is in two-halves; one of which is placed on either side of the rotating disk. Semi-elliptical recesses in the casing match with the corresponding grooves inside the rotating disk to form chambers through which a stream of water flow is maintained. When brake is operating, the water follows a helical path in the chamber. Vortices and eddy-currents are set-up in the water and these tend to turn the dynamometer casing in the direction of rotation of the engine shaft. This tendency is resisted by the brake arm balance system that measures the torque.

**Eddy current dynamometer :** This electrical absorption dynamometer operates on the principle that when an isolated conductor moves through a magnetic field, voltage is induced and local currents flow in a short circular path within the conductor. These currents, called *eddy currents* get dissipated in the form of heat.

Fig. 13.22 shows the basic components comprising and illustrating the principle of operation of an eddy current dynamometer. A toothed steel rotor is mounted onto the shaft of the test-engine and it rotates inside a smooth bored cast iron stator; the clearance between the rotor tooth and stator being very small. The stator carries an exciting coil which is energised with a direct current supplied from an external source. Further, the stator is cradled on antifriction trunnions and is provided with a brake arm to which a scale pan or spring balance is attached. The term 'cradled' means that the stator is mounted so as to permit it to swing freely about the axis of the shaft.

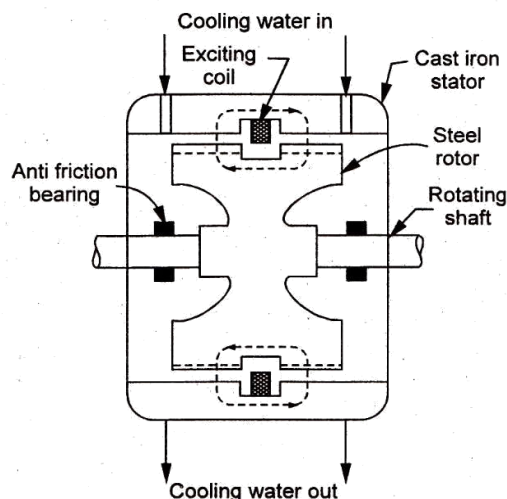


Fig. 13.22 Eddy current dynamometer

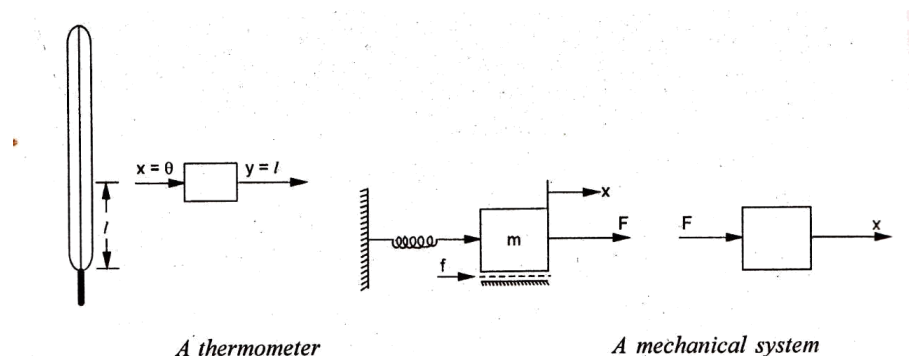
## ELEMENTS OF CONTROL SYSTEMS:



### Introduction:

A system is an assemblage of devices and components connected or related by some form of regular interaction or interdependence to form an organised whole and perform specified tasks. The system produces an output corresponding to a given input.

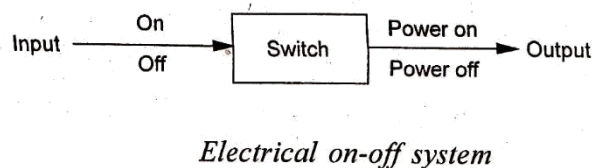
Ex: The thermometer and the mass-spring damper system can be identified as systems. The thermometer has the input  $x = \theta$  (temperature) and the output  $y = l$  (length of the mercury column in the capillary).



The term control implies to regulate, direct or command. A control system may thus be defined as;

"an assemblage of devices and components connected or related so as to command direct or regulate it self or another system".

### EX:1



19. An electrical switch which serves to control the flow of electricity in a circuit. The input signal (command) is the flipping of the switch on or off; and the corresponding output (controlled) signal is the flow or non-flow of electric current.

20. A thermal system where it is desired to maintain the temperature of hot water at a prescribed value. Before the operator can carry out his task satisfactorily, the following requirements must be met:

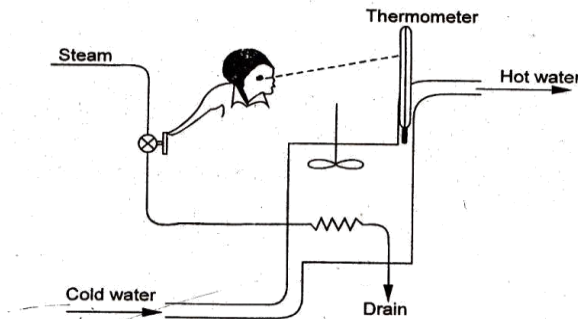
xiv. The operator must be told what temperature is required for the water. This temperature, called the set point or desired value, constitutes the input to the system.

xv. The operator must be provided with some means of observing the temperature (sensing element). For that a thermometer is installed in the hot water pipe and it measures measured temperature

compares with the desired value. This difference between the desired value and the actual measurement value is error or actuating signal.

$$e = r - c$$

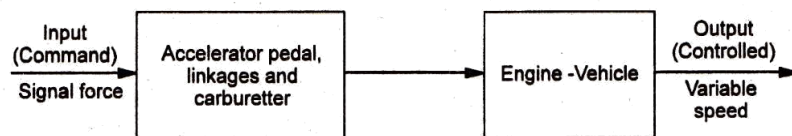
where  $r$  refers to the set-point or reference input and  $c$  denotes the controlled variable.



*Thermal system : manual feed back control*

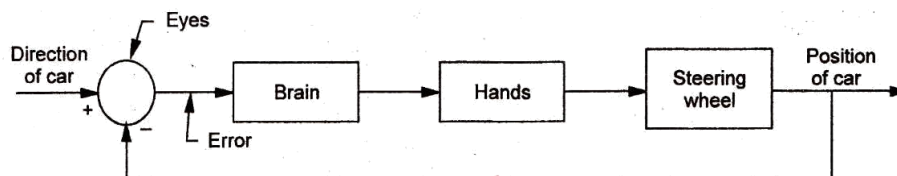
l) The operator must be provided with some means of influencing the temperature (control element) and must be instructed what to do to move the temperature in a desired direction (control function).

15. A driving system of an automobile (accelerator, carburettor and an engine vehicle) where command signal is the force on the acceleration pedal and the automobile speed is the controlled variable. The desired change in engine speed can be obtained by controlling pressure on the accelerator pedal.



*Driving system of an automobile*

15) An automobile steering system where the driver is required to keep the automobile in the appropriate lane of the roadways. The eyes measure the output (heading of the automobile), the brain and hands react to any error existing between the input (appropriate lane) and the output signals, and act to reduce the error to zero.

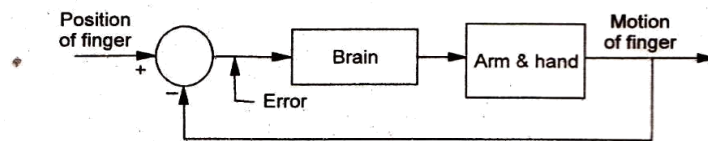


*Automobile steering system*

14) A biological control system where a person moves his finger to point towards an object. The command signal is the position of the object and the output is the actual pointed direction.



Other well-known examples of control systems are: electric frying pans, water pressure regulators, toilet-tank water level, electric irons, refrigerators and household furnaces with thermostatic control.



*Biological control system : a person pointing towards an object*

✓

### Classification of control systems:

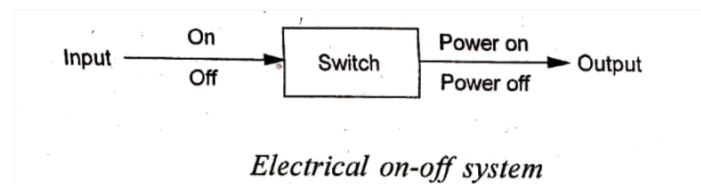
These are two basic types of control systems, 1. open loop and 2. closed loop systems.

**1 Open-loop systems (unmonitored control system).** The main features of an open loop system are:

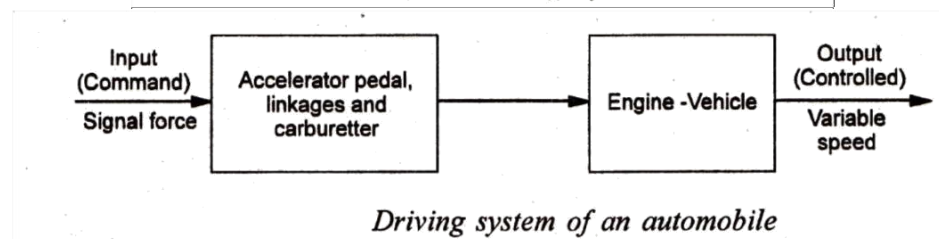
26) there is no comparison between the actual (controlled) and the desired values of a variable.

27) for each reference input, there corresponds a fixed operating condition (output) and this output has no effect on the control action, i. e., the control action is independent of output.

28) for the given set-input, there may be a big variation of the controlled variable depending upon the ambient conditions. Since there is no comparison between actual output and the desired value, rapid changes can occur in the output if there occurs any change in the external load.



*Electrical on-off system*



*Driving system of an automobile*

Some examples of open-loop system are :

☐ Trying to guide a car by setting the steering wheel, together with a pattern of subsequent changes of direction, at the beginning of a journey and making no alternation enroute as and when the car deviates from the desired path.

☐ Hitting the golf ball where the player knows his goal to get the ball into a particular hole. To achieve it, the player hits the ball correctly at the beginning of its flight. Once the moment of impact is passed, he loses his control on any further flight of the ball.

☐ The automobile traffic control signals at roadway intersections are the open loop systems. The red and green light travels (input to the control action) are predetermined by a calibrated timing mechanism and are in no way influenced by the volume of traffic (output).

**An open loop system has the following advantages and limitations:**

t) simple construction and ease of maintenance

u) no stability problems

v) convenient when the controlled variable is either difficult to measure or it is economically not feasible

w) system affected by internal and external disturbances ; the output may differ from the desired value

x) needs frequent and careful calibrations for accurate result.

**2. Closed-loop systems (monitored control systems).** The main features of a closed loop system are:

xix. There is comparison between the actual (controlled) and the desired values of the variable. To accomplish it, the output signal is fed back and the loop is completed.

xx. The error signal (deviation between the reference input the feedback signals) then actuates the control element to minimize the error and bring the system output to the desired value.

xxi. The system operation is continually correcting any error that may exist. As long as the output does not coincide with the desired goal, there is likely to be some kind of actuating signal.

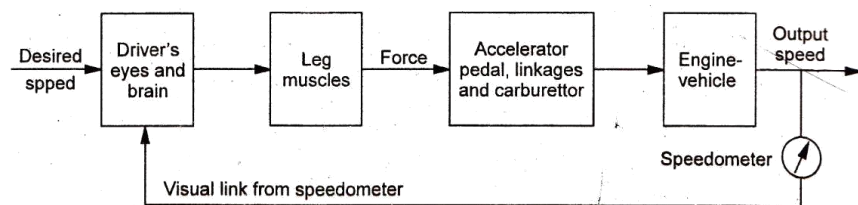
The performance of such a system is evaluated with reference to the following desirable characteristics:

□ minimum deviation following a disturbance

\*minimum time interval before return to set

point

□ minimum off-set due to change in operating conditions.



*Driving system of an automobile : manually controlled*

Examples of closed loop systems are:

24) The control of the thermal system is a closed loop, when the operator detects that the output temperature is different from the desired or reference temperature, he initiates an action to reduce the discrepancy by operating a valve that controls the steam supply to water.

25) The automobile driving system would become a closed-loop system when the driver makes a visual observation of the speed indicated by a speedometer and compares this mentally with the desired speed.

Example of automatic control systems:

13) In the automatic feed-back control of a thermal system (Fig. 15.9), the human operator has been replaced by an automatic controller. The actual temperature of the hot water is measured by a thermometer and is fed to the controller for comparison with the reference temperature whose value has been specified by appropriate, setting of the thermostat/regulator. Based on the error signal, the controller generates an output (correcting signal) which is taken to the control valve in order to change the valve opening for steam supply.

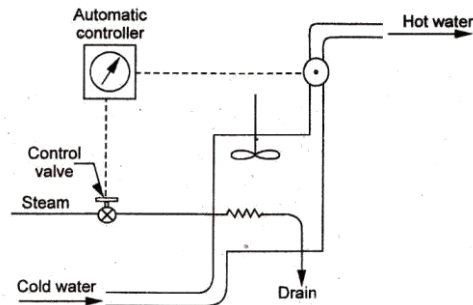


Fig. 15.9 Thermal system : automatic feed back control

(xii) The level control system depicted in Fig. 15.10 is an automatic control system. Where inflow of water to the tank is dependent on the water; level in the tank. The automatic controller maintains the liquid level by comparing the actual level with a desired level and correcting any error by adjusting the opening of the control valve.

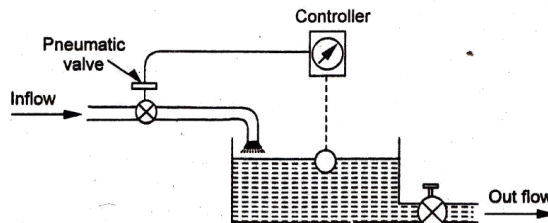


Fig. 15.10 Water-level control system

J) A pressure control system where the pressure inside the furnace is automatically controlled by affecting a change in the position of the damper (Fig 15.12).

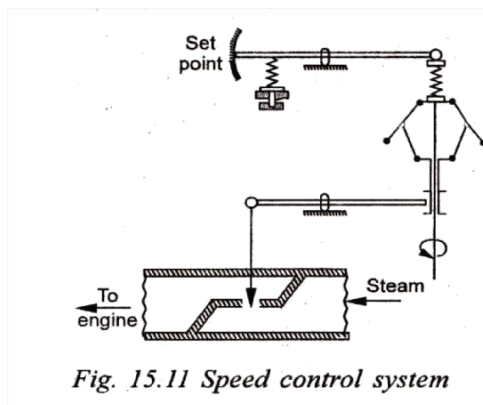


Fig. 15.11 Speed control system

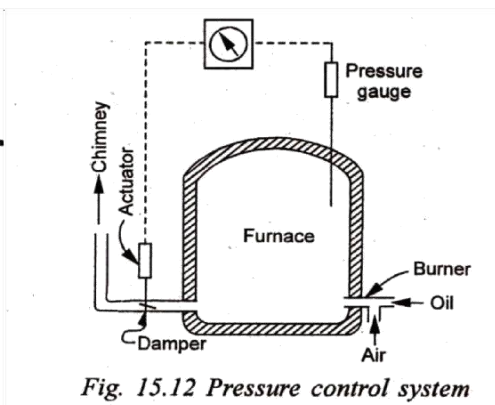


Fig. 15.12 Pressure control system

### → *Advantages and limitations of automatic control systems*

- \* suitability and desirability in the complex and fast acting systems which are beyond the physical abilities of a man.
- \* relief to human beings from hard physical work, boredom and drudgery which normally result from a continuous repetitive job
- \* economy in the operating cost due to elimination of the continuous employment of a human operator
- \* increased output or productivity
- \* improvement in the quality and quantity of the products
- \* economy in the plant equipment, power requirement and in the processing material. The feed-back permits to initiate precise control by using relatively inexpensive components
- \* reduced effect of non-linearities and distortion
- \* satisfactory response over a wide range of input frequencies.

The system has however a tendency to over-correct errors and this may cause oscillations of constant or changing amplitude.

### → **Control systems terminology**

A closed loop consists essentially of a process, error detector and control elements. Some of the terms related to these basic components are defined below :

- \* *Process, Plant or Controlled system ( $g_2$ )* : a body, process or machine of which a particular quantity or condition is to be controlled, e.g., a furnace, reactor or a spacecraft, etc.
- \* *Controlled variable ( $c$ )* : the quality or condition (temperature, level, flow rate etc) characterising a process whose value is held constant by controller or is changed according to certain law.
- \* *Controlled medium* : the process material in the controlled system or flowing through it in which the variable is to be controlled.
- \* *Command* : an input that is established or varied by some means external to and independent of the feed back control system.
- \* *Set-point or reference input ( $r$ )* : a signal established as a standard of comparison for feed back control system by virtue of its relation to command. The set point either remains constant or changes with time according to a preset programme.
- \* *Manipulated variable ( $m$ )* : the quality or condition that is varied as a function of the actuating signal so as to change the value of the controlled variable. The manipulated variable is applied to the plant  $g_2$  by the control element  $g_1$ .
- \* *Actuating signal ( $e$ )* : an algebraic sum of the reference input  $r$  and the primary feed back  $b$ . The actuating signal is also called the error or control action.



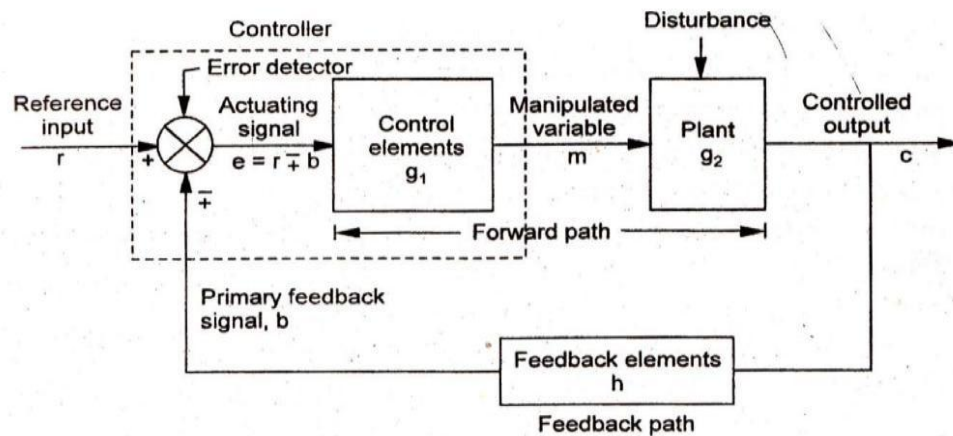


Fig. 15.13 Elements of a control system

- \* **Primary feed-back signal ( $b$ )** : a function of the controlled output  $c$ , which is compared with the reference input to obtain the actuating signal.
- \* **Error-detector** : an element that detects the feed back ; essentially it is a summing point which gives the algebraic summation of two or more signals. The direction of flow of information is indicated by arrows and the algebraic nature of summation by plus or minus signs.

Negative feed back occurs when the feed back signal subtracts from the reference signal.

$$e = r - b$$

If the feed back signal adds to the reference signal, the feed back is said to be positive.

$$e = r + b$$

Negative feed back tries to reduce the error, whereas positive feed back makes the error large.

- \* **Disturbance ( $u$ )** : an undesired variable applied to the system which tends to affect adversely the value of the variable being controlled. The process disturbance may be due to changes in set point, supply, demand, enviromental and other associated variables.
- \* **Feed-back element ( $h$ )** : an element of the feed-back control system that establishes a functional relationship between the controlled variable  $c$  and the feed back signal  $b$ .
- \* **Control element ( $g_1$ )** : an element that is required to generate the appropriate control signal (manipulated variable)  $m$  applied to the plant.
- \* **Forward and backward paths** : The transmission path from the actuating signal  $e$  to the controlled output  $c$  constitutes the forward path. The backward path is the transmission path from the controlled output  $c$  to the primary feed-back signal  $b$ .

## → Servomechanism, process control and regulators

A ***servomechanism*** is an automatic control system in which the controlled variable is mechanical position (displacement), or a time derivative of displacement such as velocity and acceleration. The output is designed to follow a continuously changing input or desired variable (demand signal). The servomechanisms are inherently fast acting (small time lag with response time in the order of milliseconds) and usually employ electric or hydraulic actuation. These systems are essentially used to control the position or speed of a mechanism which is either too heavy or too remote to be controlled manually, e.g., power assisted steering and control in large cars, aircrafts, ships etc. The complete automation of machine tools together with programmed instruction is another notable example of servomechanism.

A ***process control*** refers to the control of such parameters as level, flow, pressure, temperature and acidity of a process variable. A particular parameter has usually only one optimum desired value (set point) and the control system is required to ensure that the process output is maintained at this level in spite of changes in external conditions (load disturbances) which affect the process. The load disturbance could be (i) a change in the boiler steam pressure affecting a temperature control system (ii) a change in raw materials affecting a mixing process. The process control systems are usually slow acting (large time lags) and usually employ pneumatic actuation.

A ***regulator*** is a feed back control system in which the output (controlled variable) is maintained at a preset value irrespective of external load on the plant. The reference input or command signal, although adjustable, is held constant for long periods of time. The primary task is then to maintain the output at the desired value in the presence of disturbances (change in load on the system or changes in the environment or changes in the system itself). Examples of an automatic regulator are : regulation of steam supply in steam engines by the fly ball governor ; thermostat control of a home heating system ; control of pressure and of electrical quantities such as voltage, current and frequency.

In general a control system that regulates a variable in response to a fixed command signal is known as a regulator system whereas control system that accurately follows changes in the command signal is referred to as follow up system.

