INSTRUMENTATION AND CONTROL SYSTEMS

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UNIT-I SYLLABUS

- Definition
- Basic principles of Measurement
- Measurement systems
- Static performance characteristics
- Dynamic performance characteristics
- Sources of errors, classification, Elimination
The Instrumentation is the technology of making measurements and it implies the application of instruments for sensing, measurement, control and monitoring physical variables.

Instrumentation is a multi-disciplinary subject, its different aspects are based on the subject areas of physics, system dynamics, thermo-fluid mechanics and electrical principles.

The division of engineering science which deals with measuring techniques, devices and their associated problems is called instrumentation.
Measurement is the act, or result of a quantitative comparison between a predetermined standard and a measurand (input).

The Measurement of a given quantity is essentially an act or result of comparison between a quantity whose magnitude (amount) is unknown, with a similar quantity whose magnitude (amount) is known, the latter quantity being called a Standard.

Quantities like pressure, temperature, displacement, fluid flow and associated parameters, acoustics and related parameters, and fundamental quantities like mass, length, and time are typical of those which are within the scope of mechanical measurements.
MEASUREMENT

• Measurement is the result of an opinion formed by one or more observers about their relative size or intensity of some physical quantity.

• The opinion is formed by the observer after comparing the object with a quantity of some kind chosen as a unit called standard.

• The result of measurement is expressed by a number representing the ratio of unknown quantity to the standard.
It is more appropriate to use the term Measurement of Mechanical Quantities rather than mechanical measurements.

(i) All mechanical quantities are not measured by mechanical means.

(ii) And, measurement of mechanical quantities, in modern technology, involves the use of electrical and electronic techniques.
Measurement is the act, or result of a quantitative comparison between a predetermined standard and a measurand.

The act of measurement process produces result.
The basic requirements are:

(i) The standard used for comparison purposes must be accurately defined and should, be commonly acceptable.

(ii) The standard must be of the same character as the measurand (the unknown quantity or the quantity under measurement) and is prescribed and defined by a legal or recognized agency or organization like National Bureau of Standards (NBS) or the International Organization of Standards (ISO), the American National Standards institute (ANSI)

(iii) The apparatus used and the method adopted for the purposes of comparison must be provable.
1. **Direct Methods.** The unknown quantity is directly compared against a standard. The result is expressed as a numerical number and a unit. The standard, in fact, is a physical embodiment of a unit.

- Direct methods are quite common for the measurement of physical quantities like length, mass and time.
- As direct measurement involve human factors are less accurate, less sensitive.
- The direct methods may not always be possible, feasible and practicable.
- Hence direct methods are not preferred and are less commonly used.
2. **Indirect Methods:** The value of the physical parameter (measurand) is more generally determined by indirect comparison with secondary standards through calibration.

In direct method of measurement system consists of a transducing element which converts the quantity to be measured into an analogous signal. The analogous signal is then processed by some intermediate means and is then fed to the end devices which present the results of the measurement.
2. Indirect Methods of measurement.

Based upon the complexity of the measurement system the measurements are generally grouped into three categories.

2.1) primary measurements

2.2) secondary measurements

2.3) Tertiary measurements.
2.1 PRIMARY MEASUREMENT

• A primary measurement is one that can be made by direct observation without involving any conversion (translation) of the measured quantity into length.

• The sought value of a physical parameter is determined by comparing it directly with reference standards.

• Typical examples of primary measurements are:
  
  A. Determining the length of an object with a meter rod.
  
  B. The matching of two colors, such as when judging the color of red hot metals.
2.2 SECONDARY MEASUREMENT:

2.2 Secondary Measurements. The indirect measurements involving one translation are called secondary measurement. involves only one translation.

- Ex: the conversion of pressure into displacement by means of bellows. Conversion of force into displacement by means of spring. Therefore, a secondary measurement requires.

(i) An instrument which translates pressure changes into length changes. A length scale or a standard which is calibrated in length units equivalent to known changes in pressure.

Fig-1:
Displacement bellow convert pressure in to displacement

Fig-2: Spring convert force in to displacement
The indirect measurements involving two conversions are called tertiary measurements.

A typical example-1 of such a measurement is the measurement of temperature of an object by thermocouple.

1st translation is from temperature to voltage.

2nd translation is from voltage to length.
When static pressure (input signal) is applied to bourdon tube, its free end deflects. The deflection which constitutes the secondary signal is very small and needs to be made larger for display and reading. This task is accomplished by arrangement of lever, quadrant, gear and pointer. The amplified displacement constitutes the tertiary signal and it is indicated by the movement of the pointer against graduated scale.

1\textsuperscript{st} translation is from pressure to small displacement.

2\textsuperscript{nd} translation is from small displacement to larger displacement.
1. STATIC CHARACTERISTICS

2. DYNAMIC CHARACTERISTICS

1. STATIC CHARACTERISTICS:

- The characteristics which describe the performance of measuring instruments when subjected to low frequency inputs or DC inputs are referred to as static characteristics.

- In some of applications the parameter of interest is more or less constant or varies very slowly with time. Measurement of such applications are called static measurement.
STATIC CHARACTERISTICS OF AN INSTRUMENT:

are as follows

1.1 Accuracy
1.2 Error
1.3 Reproducibility
1.4 Drift
1.5 Sensitivity
1.6 Dead Zone
1.7 Precision
1.8 Linearity
1.9 Threshold
1.10 Hysteresis
1.11 Resolution
1.12 Stability
1.13 Range and Span
The dynamic behavior of an instrument can be determined by applying some form of known and predetermimed input to its primary element and study the output i.e., movement of pointer)

Generally the behavior is judged for 3 types of inputs.

1. Step change: In this case the input having changed remains constant.
2. Linear change: In this case the input changes linearly with time.
3. Sinusoidal change: In this case the magnitude of the input changes in accordance with a sinusoidal function of constant amplitude.
The dynamic characteristics of an instrument are as follows:

2.1 Speed of response
2.2 Measurement Lag
2.3 Fidelity
2.4 Dynamic error
2.5 Dynamic range
2.6 Band width
2.7 Setting time
2.8 Time constant.
There is another way in which instruments or measurement systems may be classified.

This classification is based upon the functions they perform.

The three main functions are explained below:

1) Indicating Function.
2) Recording Function.
3) Controlling Function.
(i) Monitoring of processes and operations.
(ii) Control of processes and operations.
(iii) and Experimental Engineering analysis.
Generalized configuration and functional description of measuring instruments-Examples

Sources of error,

Classification & elimination of error
Most measuring systems fall within the framework of a general arrangement consisting of three phases or stages.

- **Stage-1**: A detector – transducing or sensor stage.
- **Stage-2**: An intermediate stage: (Signal conditioning stage)
- **Stage-3**: A terminating or Read out stage.

![Block diagram of the Generalized Measuring System](image)
It consists of a cylinder and piston, a spring resisting piston movement, and stem with scale divisions.

As air pressure bears against the piston, the resulting force compresses the spring until spring & air forces balance. The calibrated system which remains in place after the spring returns the piston, indicates the applied pressure.

The piston-cylinder combination constitutes a force summing apparatus, sensing and transducing pressure to force.

As a secondary transducer, the spring converts the force to a displacement. Finally, the transduced input is transferred without signal conditioning to the scale & index for read out.
Figure 2.1 Bourdon-tube pressure gage as the generalized measurement system.
A generalized configuration in instruments and measurement systems which brings out a significant input-output relationship present in them is shown in Figure. Input quantities are classified into three categories:

(i) Desired inputs.

(ii) Interfering inputs.

(iii) Modifying inputs.

...
Generalized input-output configuration of measurement systems.
• Error = Reading of standard value – measured value

• The accuracy and precision of an instrument depends upon its design, the material used and workmanship that goes into making the instrument.

• The choice of an instrument for a particular application depends upon the accuracy desired.

• If only a fair degree of accuracy is desired, it is not economical to use expensive meter and skill for the manufacture of the instruments.

• But an instrument used for an application requiring a high degree of accuracy has to use expensive and a highly skilled workmanship.
No measurement can be made with perfect accuracy, but it is important to find out what accuracy actually is and how different errors entered into the measurement. Errors may arise from different sources and are usually classified as under.

1) Gross Errors
   1.1) Instrument Errors

2) Systematic Errors
   2.2) Environmental Errors

3) Random Errors
   2.3) Observational Errors
1. **Noise:** it is defined as any signal that does not convey useful information. The noise or signal disturbances contribute to the uncertainty of measurement.

   Noise may originate either
   - At the primary sensing device
   - In a communication channel
   - In the indicating element of the system
   - Noise can be reduced to a maximum level through filtering, careful selection of components, shielding and isolation of the entire measuring system.

2. **Response time:** measuring system can not immediately indicate the input signal applied to it. This factor contributes to uncertainty. (mercury thermometer)
3. **Design limitations:** In the design of an instrument, there are certain inevitable factors which lead to uncertainty of measurement.

4. **Effects of friction in the instrument movement:**

5. **Effect of resolving power:** The ability of observer to distinguish between nearly equal divisions.

6. **Energy exchanged by interaction:** Whenever energy required for operating the measuring system is extracted from the measurand, the value of latter is altered to a greater or lesser extent.
7. Transmission: In the transmission of information from primary sensing element to indicator.

8. Deterioration of measuring system: it is due to physical or chemical deterioration or other alterations in characteristics measuring elements.

9. Ambient influences on measuring system: The changes in atmospheric temperature may alter the elastic constant of a spring, changes in resistance. Other factors like humidity, pressure.

10. Errors of observation and interpretation: Mistakes in observing, interpreting, recording the data. (Parallax errors, personal observer
This unit covers

• MEASUREMENT OF DISPLACEMENT
• MEASUREMENT OF TEMPERATURE
• MEASUREMENT OF PRESSURE.
As per syllabus we focus on following.

Theory and construction of various transducers to measure displacement.

- Piezo electric transducer
- Inductive transducer
- Capacitance transducer
- Resistance transducer
- Ionization transducer
- Photo Electric transducer
- Calibration procedure
A transducer is a device which senses the physical variable to be measured and converts into a suitable signal (voltage or current).

A device to convert the quantity or phenomenon to be measured into a voltage or current, which can be observed on an oscilloscope, read on a meter or recorded on a chart.

Ex: - Pressure transducer
  - Temperature transducers: (RTD, Thermistor, Thermocouple, Pyrometer)
- Displacement transducers:
  1) Variable resistance transducer, 2) LVDT
  3) Capacitive, 4) variable reluctance displacement transducer,
  5) piezoelectric transducer,
  6) Hall effect displacement transducer,
  7) photoelectric transducer, 8) Ionization transducer, 9) LDR
Examples of Displacement transducers:

1) Variable resistance transducer,
2) LVDT
3) Capacitive,
4) variable Reluctance displacement transducer,
5) piezoelectric transducer,
6) Hall effect displacement transducer,
7) photoelectric transducer,
8) Ionization transducer,
9) LDR
1. **Fundamental parameters**: these include
   a) Type of measurand (input)
   b) Range of measurement
   c) Required precision, which includes
      - allowable non-linearity effects
      - allowable dead-zone effects
      - Frequency response
      - Resolution

2. **Environment**: This includes conditions of
   a) Ambient temperature
   b) Corrosive or non-corrosive atmosphere
   c) What shock and vibration to withstand
FACTORS ON WHICH TRANSDUCER SELECTION DEPEND

3. **Physical conditions**: These are
   a) Room or available space to mount the transducer.
   b) Whether the measurement is static or dynamic.
   c) How much energy can be extracted from the input to do measurement without much loading.

4. **Compatibility with next stage**: Transducer should be so chosen so as to meet the requirements of next stage.
   a) Impedance matching.
   b) Excitation voltage matching.
   c) Sensitivity tolerance matching.
5) General requirements:
   a) Ruggedness to withstand over loads
   b) Linearity
   c) Repeatability
   d) Stability and reliability
   e) Good dynamic response
   f) Convenient instrumentation.
Transducers are classified as follows:

1. Active and passive transducer and Passive transducer.

**Active Transducer**: The transducer which do not require any external excitation energy to provide their output are known as active transducer.

Example: Piezo electric transducer
- Photo voltaic cell
- Thermocouple
- Moving coil generator
1b) **Passive transducer**: The transducers which require an external excitation energy to provide their output are known as passive transducers.

Examples: - Resistance transducer  
- Capacitive transducer  
- Inductive transducer  
- Hall-effect transducer  
- Photo emissive cell  
(Photovoltaic type transducer)
2) **On the basis of transduction principle used:** the input variable to the transducer is being converted into resistance, capacitance or inductance value.

2a) **Resistive transducers:**
   - Resistance thermometer, Potentiometer device,
   - Resistance strain gauge, Thermistor,
   - Photo conductive cell

2b) **Capacitive transducers:** Dielectric gauge,
   - capacitor microphone, Variable capacitance pressure gauge

2c) **Inductive transducers:** Differential transformer type transducer (LVDT, RVDT), Reluctance type transducer,
3) Primary and secondary transducers:

3a) Primary transducer: is the first element in a measurement system and it senses the physical parameters (like temperature, pressure, displacement, force etc.) and converts them into a mechanical parameter (usually displacement). These are mechanical type and electrical type.

Ex: - pressure sensing elements (diaphragm, bellows, bourdon tube)
- solid rod expansion thermometers (Bimetallic strip)
- The cylindrical column of a load cell which converts displacement into strain.
3) Primary and secondary transducers:

3b) Secondary transducer: A transducer which is used as the second element of a measurement system, to convert the mechanical output of primary transducer into an electrical quantity is known as secondary transducer. Generally these are electrical type transducers.

Example: -strain gauge

-LVDT (Linear variable differential transformer).
4) Analog and Digital transducers:

4a) Analog transducer: It is a transducer which produces an output in analog form or a form which is a continuous function of time.

Example: - Thermistor
- Thermocouple
- Strain gauge
- LVDT

4b) Digital transducer: It is a transducer which produces an output in digital form or in the form of pulses.

Example: Turbine flow meter.
5) Transducers and Inverse Transducers:

5a) Transducer (Input transducers): a measuring device which measures and converts non-electrical quantity into electrical quantity is known as transducer. Such transducers are usually used in the input stage of a system and hence they are also known as input transducers.

Example: - potentiometer
- Thermo couple
- LVDT
- Moving coil generator
5) Transducers and Inverse Transducers:

5b) Inverse Transducer (output transducers): A measuring device which measures and converts an electrical quantity into non-electrical quantity is known as inverse transducer. Such transducers are usually placed at the output stage of a measurement system and hence they are also known as output transducers. Inverse transducers are used in feedback measuring systems like servo-mechanism etc.

Example: - Piezo electrical crystal

- Data indicating and recording instruments (Analog ammeter, Volt meter, pen recorders etc.)
1a) Variable resistance transducer (Potentiometer)
2a) Variable inductance transducer – LVDT (Linear Variable Differential Transducer)
3) Variable reluctance displacement transducer.
4a) Linear Variable capacitance transducer
5) Piezo electric transducer
6) Light dependent Resistance (LDR)
7) Ionization transducer
1b) Angular potentiometric displacement transducer
2b) Variable inductance transducer – RVDT
   (Rotary variable differential transformer)
3b) Angular variable capacitance transducer
4) Hall-effect angular displacement transducer
5) Synchro’s and Resolver’s
1a) VARIABLE RESISTANCE TRANSDUCER (Potentiometer)
1B) ANGULAR-POTENTIOMETRIC DISPLACEMENT TRANSDUCER
2B) VARIABLE INDUCTANCE TRANSDUCER
(Ex. LINEAR VARIABLE DIFFERENTIAL TRANSFORMER LVDT)
2B) ROTARY VARIABLE DIFFERENTIAL TRANSFORMER
3) VARIABLE RELUCTANCE DISPLACEMENT TRANSUDUCER

Transducers of variable reluctance consists of:

- Target (Iron Core)
- Core
- Air Gap
- Displacement $x_i$
- Output
4A) CAPACITIVE TRANSDUCER USING THE EFFECT OF VARIATION OF OVERLAPPING AREA OF PLATES.
The capacitive transducer working on the principle of change in capacitance due to variation of dielectric constant w.r.t linear displacement is shown in figure. It contains two fixed plates.

\[ C = \varepsilon_r \varepsilon_0 \frac{A}{d} \]
5. PIEZO-ELECTRIC TRANSDUCER

[Diagram showing a piezoelectric crystal with annotations for force, electrodes, output voltage, and mechanical and electrical properties.]
IONIZATION TRANSDUCER: TO MEASURE DISPLACEMENT

\[ x, x = \text{Internal electrodes} \]
\[ y, y = \text{External electrodes} \]
\[ x = \text{displacement} \]
\[ E_{out} = \text{potential difference} \]
LIGHT DEPENDENT RESITOR (LDR):
Hall effect: relates to the generation of transverse voltage difference on a conductor which carries current and is subjected to magnetic field in perpendicular direction.
HALL-EFFECT DISPLACEMENT TRANSDUCER
1A). LIQUID-IN-GLASS THERMOMETER

[Diagram of a liquid-in-glass thermometer with labeled parts: safety bulb, capillary tube, stem, scale, and temperature sensing bulb.]
1b) GAS THERMOMETER
1c) VAPOUR PRESSURE THERMOMETER
SPIRAL SHAPED BIMETALLIC STRIP THERMOMETER

- Pointer
- Calibrated scale
- Spiral shaped bimetallic strip
Thermistors are made in different sizes and forms (shapes) such as beads, discs, rods and probes as shown in fig.
WORKING OF THERMISTOR  ..contd.

Fig: Measurement of temp using thermistor
Here the change of resistance is displayed by the output device and the displayed signal gives the measurement of the temperature of the process when calibrated. The resistance temperature characteristics of thermistor are illustrated in figure
## DISTINGUISH BETWEEN RTD & THERMISTOR

### RTD

1. RTD are made of pure metals
2. It has +ve temp. Coefficient
3. RTD has low accuracy
4. Used for greater temp range up to 600\(^0\)C
5. RTD allow smaller cable lengths
6. Slow output response
7. Used in industrial installation application
8. Good stability
9. These are expensive
10. Low amount of heating

### THERMISTOR

1. Thermistors are made up of ceramic or polymer materials.
2. It has –ve temp. coefficient
3. Thermistors have good accuracy
4. Used for lower temp range up to 130\(^0\)C
5. It allows larger cable length
6. Fast output response
7. Used in home appliances
8. Less stable than RTD
9. These are inexpensive
10. High amount of self heating
If a circuit is formed including thermocouple as shown in figure. A minimum of two conductors will be necessary resulting in two junctions P, Q. If we disregard the Thomson effect, the net emf will be result of the difference between the two Peltier e.m.f’s occurring at the two junctions.
As shown in fig(a), if the third metal ‘C’ is introduced and if the new junctions ‘r’ and ‘s’ are both held at temperature \( T_3 \), the net potential for the circuit will remain unchanged.

This of course permits insertion of a measuring device or circuit without upsetting the temperature function of the thermocouple circuit.
As shown in fig(b), if the third metal ‘C’ may be introduced at either a measuring or reference junction, so long as couples $P_1$ and $P_2$ are maintained at the same temperature $T_1$.

this makes possible the use of joining metals, such as soft or hard solder in fabricating the thermocouples.
If a simple thermocouple circuit develops an emf $e_1$ when its junctions are at temperatures $T_1$ and $T_2$, and an emf $e_2$ when its junctions are temperatures $T_2$ and $T_3$, it will develop an emf $(e_1 + e_2)$, when its junctions are at temperatures $T_1$ and $T_3$. 

\[ \text{Fig (b)} \]
When two metals which are made up of two different materials are joined together to form two junctions. One junction senses the desired or unknown temperature, this junction is called hot or measuring junction. The second junction will be usually be maintained at a known or fixed temperature and is called cold or reference junction.

When the measuring junction is heated up with respect to other junction, the emf developed at the junction is proportional to the applied temperature and the junction temperature is known as thermocouple.
The thermocouple hot Junction will be exposed to the process or media where the temperature has to be measured. The thermocouple cold junction will be maintained at a constant reference temperature.
COMMON METHODS FOR SEPARATING THERMOCOUPLE WIRES

Fig. 10.27.

Element with double-bore insulators

Element with asbestos insulation

Element with bead insulator

Bare element
TOTAL RADIATION PYROMETER (MIRROR TYPE)
OPTICAL PYROMETER

(i) Dark image  (ii) Bright image  (iii) No image (Disappeared image)
1) **Atmospheric pressure** ($P_{at}$): this is the pressure exerted by the envelope of air surrounding the earth surface.

$$P_{at} - P_{vp} = \rho gh$$

- $P_{vp}$ = mercury vapour pressure
- $h$ = mercury level
- $P_{at}$ = Atmospheric presure
- $\rho$ = density of mercury

Since mercury has a low vapour pressure,

$$P_{at} = \rho gh$$
2) Absolute Pressure \( (P_{\text{ab}}) \) : It is defined as the algebraic sum of atmospheric pressure and gauge pressure.

\[
P_{\text{abs}} = P_{\text{atm}} + P_{\text{gauge}} \quad (\text{for positive gauge pressure})
\]

\[
P_{\text{abs}} = P_{\text{atm}} + (-P_{\text{gauge}}) = P_{\text{atm}} - P_{\text{gauge}} \quad (\text{for negative gauge pressure})
\]

3) Gauge Pressure \( (P_{\text{gauge}}) \): The pressure above atmospheric pressure is called gauge pressure.

When the unknown pressure is more than atmospheric pressure, the pressure recorded by the instrument is called gauge pressure.
4. Vacuum Pressure: The pressure below atmospheric pressure is called vacuum pressure or negative pressure.

Fig: Relation between Pressure terms:
1. Gravitational transducers:
   a) A dead weight tester/gauge
   b) Manometers
      B. 1) well type manometer
      B. 2) U type manometer (differential manometer)
      B. 3) Barometer
      B. 4) Inclined manometer
      B. 5) Micro manometer.

2. Elastic transducers:
   2.1) Bourdon pressure gauge
   2.2) Elastic diaphragm gauges
      - Flat type diaphragm gauge
      - Corrugated type diaphragm gauge
   2.3) Bellow gauges
3. Strain gauge Pressure cell :
   - Pinehed tube
   - Cylindrical tube pressure cell
   - Flattened tube pressure cell

4. Mcleod gauge

5. Thermal conductivity gauges :
   - Thermocouple gauge
   - Pirani gauge

6. Ionization gauges:

7. Electrical resistance pressure gauge:
DEAD-WEIGHT TYPE TESTER OR GAUGE (PISTON GAUGE)
B) DIFFERENT TYPES OF MANOMETERS

B. 1) Well type manometer
B. 2) U type manometer (differential manometer)
B. 3) Barometer
B. 4) Inclined manometer
B. 5) Micro manometer.
WELL TYPE MANOMETER:

It consists of a well and a tube. The area of the well is much larger than the area of the tube. So when pressure $P_a$ is applied on well, and pressure $P_b$ is applied in a monometer. The pressure difference will be indicated by the height of the liquid column in the tube.

Pressure difference $= P_d = P_a - P_b = \rho \ h \ g$

$\rho$ = density of fluid

$h$ = net column height

$g$ = local gravity acceleration

The height becomes a measure of the applied pressure when calibrated.

The accuracy of the instrument is low.
A barometer is a single leg instrument in which one end of the liquid column is kept at zero absolute pressure.

\[ P_{\text{at}} - P_{\text{vp}} = \rho gh \]

\( P_{\text{vp}} = \text{mercury vapour pressure} \), \( P_{\text{at}} = \text{atmospheric pressure} \)

\( h = \text{height of liquid column} \), \( g = \text{local gravity acceleration} \)

Mercury has a low vapour pressure and thus can be neglected in comparison to \( P_{\text{at}} \)

\[ P_{\text{at}} - 0 = \rho g h \Rightarrow P_{\text{at}} = \rho g h \]

Then the height of the liquid column is a measure of the absolute pressure.

To achieve high accuracy, the zero level of the well is set at the zero level of the scale before taking each reading.
In this type, the tube is tilted with respect to gravity. This increases the sensitivity of the manometer as a greater motion of liquid is possible along the tube for a given change in vertical height. (as the inclined tube will have more graduations per unit vertical height. The inclination of tube is around 10 degrees.)
U-TUBE MANOMETER
( DIFFERENTIAL MANOMETER)

• U tube manometer is the most simple and most commonly used manometer for measurement of differential pressure between two points.

• A U-tube manometer consists of two vertical columns as shown in figure. The manometer tube is filled with a liquid (usually mercury).

• Before application of pressure, the liquid in the two columns is at same level, because both the columns are subjected to atmospheric pressure at ideal state.
MICRO MANOMETER:

[Diagram showing a micro manometer with labeled parts: Micrometer, Well, Flexible tube, P_b, P_a, Magnifier]
DIFFERENT DIAPHRAGMS

Flat Diaphragm for Absolute Pressure Measurement

\[ P = (P_1 - P_2) \]

Flat Diaphragm for Differential Pressure Measurement

Corrugated Diaphragm

Corrugated Diaphragm in Capsule Form

Figure (1): Different Forms of Diaphragms
A) USE OF RESISTANCE STRAIN GAUGE WITH FLAT DIAPHRAGMS:

Principle: a obvious approach is to simply apply gauges directly to a diaphragm surface and calibrate the measured strain in terms of pressure.

• In this set up one gauge is subjected to tension while the other gauge senses compression. When pressure is applied to the side opposite the gauges, the central gauge is subjected to tension while the outer gauge senses compression. The two gauges are used in adjacent bridge arms, thereby adding individual outputs and simultaneously providing temperature compensation.
B) USE OF INDUCTIVE TYPE TRANSDUCER WITH FLAT DIAFRAGMS:

- Variable inductance is used as a form of secondary transducer used with a diaphragm.
- In inductive type of secondary transducer the flexing of the diaphragm is utilized to change the relative induction of two coils placed in the magnetic field.
- The device consists of two E-shaped magnetic pieces placed equally around a diaphragm. Two coils are wounded around these E-shaped pieces.
The fig. illustrates the principle of operation of a diaphragm pressure gauge.

Because of pressure differential, the diaphragm deflects.

The mechanical linkages arrangement shows the deflection of indicator on the pressure scale and corresponding pressure is measured.
ii) PRESSURE MEASUREMENT WITH BELLOWS:

- Bellows, the pressure measuring elements are formed by the series combination of capsules. The working principle of bellow is same that of diaphragms; ie the applied displacement is converted into proportionate mechanical displacement.
- The materials used to construct bellows are brryllium copper, brass, monel, stainless steel and nickel.
- When ever the pressure to be measured is applied to the sealed end of bellow, suffers displacement. The generated displacement can be known by attaching a pointer scale arrangement to the sealed end by transmitting the displacement to the secondary transducer.
III) BOURDON TUBES

The bourdon tubes are available in different shapes such as spiral, helical, twisted and C shaped. However all the tubes have non-circular cross-section. The materials used in the construction of bourdon tubes are brass, steel and rubber.
DIFFERENT TYPES OF BOURDON ELEMENTS

- **Spiral**

- **Helical**

- **Twisted tube**

- **Fixed pivot point**

- **Axis**

- **Small angular displacement**

- **Applied pressure, P**
Pressure is applied to one side of the bellows and the resulting deflection is counter balanced by a spring.

By suitable linkages, the bellows displacement is magnified and the gauge pressure is indicated by a pointer on the scale.

Therefore, the value of applied pressure is directly read from the calibrated scale.
THE ARRANGEMENT OF BELLOWS TYPE PRESSURE GAUGE FOR INDICATING DIFFERENTIAL PRESSURE.

Fig. 8.33 Bellows pressure gauge

Fig. 8.34 Differential bellows gauge
ELASTIC DIAPHRAGAM TYPE PRESSURE GAUGE
WORKING OF BOURDON GAUGE
Flattened tube pressure cell is a type of strain gauge pressure cell. A strain gauge pressure cell works on the principle that any container will undergo strain (change in its dimensions), when it is subjected to internal pressure. As strain is proportional to the applied pressure, the measure of strain provides the measure of the applied pressure. Pressure cell is shown in figure.
MCLEOD GAUGE
IIA) THE PIRANI-TYPE THERMAL CONDUCTIVITY GAUGE FOR LOW PRESSURE MEASUREMENT
IIB) THERMOCOUPLE TYPE CONDUCTIVITY GAUGE
IIB) THERMOCOUPLE TYPE CONDUCTIVITY GAUGE
IONIZATION GAUGE FOR MEASUREMENT OF VERY LOW PRESSURE
DERIVE AN EQUATION FOR DIFFERENTIAL PRESSURE BASED ON THE MOVEMENT OF LIQUID IN THE INCLINED COLUMN ONLY
SYLLABUS:

DIRECT METHODS:

INDIRECT METHODS:

Capacitive, ultrasonic, magnetic, bubbler level, Cryogenic fuel level indicator
In the modern manufacturing industries which uses many solvents, chemicals, steam and other liquids.

Power plants use vast amount of water, the accurate measurement of liquid is very essential.
A) **DIRECT METHODS**: which uses the varying level of the liquid as a means of obtaining the measurement. The response of the device indicates the changes in liquid level directly.

A1) sight glass level gauge
A2) Bob and tape method
A3) hook type level gauge
A4) Float level indicator
A5) float and shaft liquid level gauge
A6) Displacer type liquid level measuring instrument
   - Torque tube displacer
   - Spring balance displacer
B) INDIRECT METHODS

In indirect methods of level measurement methods, uses a variable (resistance, capacitance, inductance, buoyancy force, hydrostatic pressure) that changes with the liquid level to actuate measuring mechanism. Thus the change occurred in these parameters gives the measure of liquid level.

B1) Capacitive type level indicator.
B2) Float operated potentiometer (Electrical resistance
B3) Ultrasonic level measurement instrument.
B4) Bubbler (Purge) type level indicator
B5) Magnetic type level indicator
B6) Radioactive method for level measurement.
B7) cryogenic fuel level indicator.
DIRECT METHODS
A1) SIGHT GLASS LEVEL GAUGE
A2 ) BOB AND TAPE METHOD
A3) HOOK TYPE LEVEL GAUGE
A4) FLOAT TYPE LEVEL INDICATOR
A5) FLOAT & SHAFT LEVEL GAUGE
I) TORQUE TUBE DISPLACER
II) SPRING BALANCE DISPLACER
B1) CAPACITIVE TYPE LEVEL INDICATOR.
B2) FLOAT OPERATED POTENTIOMETER (ELECTRICAL RESISTANCE) LEVEL INDICATOR
B3) ULTRASONIC LEVEL MEASUREMENT INSTRUMENT
B4) BUBBLER (PURGE) TYPE LEVEL INDICATOR

![Diagram of a bubbling level indicator with a pressure gauge, air flow meter, and pressure regulator.](image)

- **Pressure gauge** labeled as $(p \propto h)$
- **Air supply** connected to the air flow meter
- **Pressure regulator** adjusting the pressure
- **Level, h** indicating the depth of the bubbling reservoir
- **Pressure, P** measured by the pressure gauge
B5) MAGNETIC TYPE LEVEL INDICATOR
B6) RADIOACTIVE (NUCLEAR RADIATION) METHOD FOR MEASUREMENT OF LEVEL
B8) CRYOGENIC FLUEL LEVEL INDICATOR
Syllabus:

- Rotameter
- Magnetic flow meter
- Ultrasonic flow meter
- Turbine flow meter
- Hot-wire anemometer
- Laser Doppler Anemometer (LDA)
FLOW MEASURING INSTRUMENTS

1) Rotameter (Variable area flow meter)
2) Magnetic flow meter
3) Turbine flow meter
4) Hot wire anemometer (Thermal method)
5) Ultrasonic flow meter
6) Laser Doppler Anemometer (LDA)
1. ROTAMETER
2. MAGNETIC FLOW METER
3. TURBINE FLOW METER ..contd.
HOT WIRE ANEMOMETER
4.1) CONSTANT CURRENT METHOD OF HOT WIRE ANEMOMETER
4.2) CONSTANT TEMPERATURE METHOD OF HOT WIRE ANEMOMETER
5) WORKING OF LASER DOPPLER ANEMOMETER
6. ULTRASONIC FLOW METER

(a) $V_s + V$

ULTRASONIC FLOW METER

DIAGRAM FOR BASIC PRINCIPLE

FLOW

UPSTREAM

DOWNSTREAM

$T = TRANSMITTER$

$R = RECEIVER$

$X$
6) ULTRASONIC FLOW METER

1. TRAVEL TIME DIFFERENCE METHOD
2. FREQUENCY DIFFERENCE METHOD
2. FREQUENCY DIFFERENCE METHOD

![Diagram of a frequency difference method circuit with symbols T1, R1, T2, R2, V_s + V, V_s - V, and an amplifier and pulse generator.]

(c)
END OF MID-1 SYLLABUS
In this we study

Mechanical Tachometers

Electrical tachometers –
- Stroboscope,
- Noncontact type of tachometer
TACHOMETER: An instrument used to measure angular velocity of shaft by registering, the number of rotations during the period of contact, or by indicating directly the number of rotations per minute.
MECHANICAL TACHOMETERS

1. Hand speed indicator
   i. revolution counter & timer
   ii. Tachoscope tachometer
   iii. Hand speed indicator
2. Centrifugal force tachometer
3. Vibrating read tachometer
4. slipping clutch tachometer
1 Drag cup tachometer (eddy current)
2 Tacho generators
   i. DC tachometer generator
   ii. Ac tachometer generator
3. Commutated capacitor tachometer
4. Contactless tachometer (non-contact type)
   i. Inductive pickup tachometer
   ii. Capacitive type pickup tachometer
   iii. Photo electric tachometer
   iv. Stroboscope
1.1 REVOLUTION COUNTER
1.3 HAND SPEED INDICATOR
2 CENTRIFUGAL FORCE TACHOMETER (FLY BALL TACHOMETER)
3 VIBRATING REED TACHOMETER:

The diagram illustrates the principle of a vibrating reed tachometer. It shows a scale with frequency markings: 1500, 1600, and 1700. The middle section, labeled "Vibration," indicates the reed's vibration frequency of 1640. Arrows and labeled sections show the "No vibration" states at the beginning and end of the scale. The right side of the diagram depicts the mounting block and tuned reeds.
4. SLIPPING CLUTCH TACHOMETER
2.1 DRAG CUP TACHOMETER
(EDDY CURRENT TACHOMETER)
2.2 TACHO GENERATOR

2.2.1 AC TACHOMETER GENERATOR
2.2 DC TACHOMETER GENERATOR
2.3 COMMUTATED CAPACITOR TACHOMETER
CONTACTLESS TACHOMETER
(NON-CONTACT TYPE) TACHMETER

2.4.1 INDUCTIVE PICKUP TACHOMETER
CONTACTLESS TACHOMETER (NON-CONTACT TYPE) TACHOMETER
2.4.3 PHOTO ELECTRIC TACHOMETER

2.4.3.1 PHOTO ELECTRIC PICK-UP TACHOMETER

[Diagram of a photoelectric tachometer with labels for lamp, lens to focus light, reflecting surface, non-reflecting surface, photo-electric cell, and output.]
2.4.3 PHOTO ELECTRIC TACHOMETER

2.4.3.2 ROTATING PHOTO-ELECTRIC TACHOMETER

[Diagram of a rotating photo-electric tachometer with labeled components: Light sensor, Light, Output, Perforated disk, Shaft, Rotating component.]
MECHANICAL DISK-TYPE STROBOSCOPE
ELECTRICAL STROBOSCOPE
Vibration: vibration refers to the repeated cyclic oscillations of a system. The oscillatory motions may be simple harmonic (sinusoidal) or complex (non-sinusoidal).

vibration: if the displacement–time variation is of a generally continuous form with some degree of repetitive nature, it is thought of being a vibration.
DISADVANTAGES OF VIBRATION

- Temperature. For example, a $10^0$ C increase in temperature of a ball bearing is said to Abnormal vibrations in machine cause accelerated wear. Even a small insignificant increase in the level of vibration causes a sharp increase in bearing wear as result of raising reduce the service life of bearing by half.

- Vibrations in peripheral machine parts can cause permanent damage attributable to fatigue in welds and bolted joints.

- Increased vibrations levels in a machine will lead to operational difficulties sooner.
COMMON CAUSES OF VIBRATION

- Imbalance of machine
- Resonances: occurs when the speed of machinery equals to its natural frequency of vibration. This can be eliminated by decreasing or increasing the mass or the spring constant.
- Misalignment.
- Mechanical & electrical asymmetry
- Use of wrong ball bearing
FOR LINEAR MOTION:
- Displacement \( S = f(t) \)
- Velocity \( V = \frac{ds}{dt} \)
- Acceleration \( a = \frac{dv}{dt} = \frac{d^2t}{dt^2} \)
  linear jerk \( = \frac{da}{dt} \)

FOR ANGULAR MOTION:
Angular displacement \( \Theta = g(t) \)
Angular velocity \( \Omega = \frac{d\Theta}{dt} \)
Angular acceleration \( \alpha = \frac{d\Omega}{dt} = \frac{d^2t}{dt^2} \)
Angular Jerk \( = \frac{d\alpha}{dt} \)
Vibrometer: A vibrometer is a device used for measurement of vibrations.

Accelerometer: A accelerometer is a device used for measurement of acceleration.
1. Vibration wedge:
ii. Cantilever or Reed type vibrometer:
i. Acceleration level indicator:
ELEMENTARY ACCELEROMETERS
TYPES OF ACCELEROMETERS USED FOR MEASUREMENT ACCELERATION:

i. Piezo-electric type accelerometer
ii. Seismic type accelerometer

I. Piezo-electric type accelerometer:
SIESECIC ACCELEROMETER (DISPLACEMENT SENSING)

\[ x_1 = x_0 \cos \omega t \]
I. Strain gauge accelerometer
II. Variable resistance vibration sensor
III. Piezo-electric accelerometer’
IV. LVDT accelerometer
V. Capacitive vibration sensor
VI. Inductive vibration sensor
I. STRAIN GAUGE ACCELEROMETER

Diagram showing a strain gauge accelerometer with a cantilever, mass, strain gauges, and a housing filled with fluid to provide damping.
VARIABLE RESISTANCE VIBRATION SENSOR
(a simple potentiometric vibration sensor)
II. PIEZOELECTRIC ACCELEROMETER
III. LVDT ACCELEROMETER
iv. CAPACITY SENSOR (CAPACITY ACCELEROMETER)
iv. CAPACITY SENSOR (CAPACITY ACCELEROMETER)
V. VARIABLE INDUCTION TYPE ACCELEROMETER
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.
A strain gauge is a strain transducer, i.e., device for measuring dimensional changes on the surface of a structural member under test.

Importance of strain measurement:

1. As a means of determining maxi. stress values
2. To avoid the use of large factor of safety in the design of aircraft, automatic control equipment due to mass/inertia considerations.
3. For experimental verification of strain in complex physical systems.
I: Mechanical Strain gauges (Extensometers)

II. Electrical strain gauges: mechanical strain gauges are replaced with electrical strain gauges. The capability to measure dynamic conditions at very frequencies.

III. photo-elastic
While designing any strain gauge the following points are need to be considered for an accurate measure of strain:

i. Extremely small size and negligible mass
ii. Simple and easy attachment to the specimen under test
iii. High speed of response.
iv. High sensitivity in the direction of measured strain.
v. Capability to indicate static, dynamic strain.
vi. In sensitive to ambient conditions (temp, humidity, vibration)
vii. Inexpensive.
viii. Availability in various types & sizes.

All above are fulfilled by the bonded resistance strain gauges.
Applications: used to measure force, pressure, acceleration, torque.

Measurement at remote location is possible.

Used in control engineering applications.

Advantages:

it has all the requirements shown above.

i. Extremely small size and negligible mass

ii. Simple and easy attachment to the specimen under test

iii. High speed of response.

iv. High sensitivity in the direction of measured strain.

v. Capability to indicate static, dynamic strain.
1. Grid type strain gauge
FOIL TYPE STRAIN GAUGE
SEMICONDUCTOR GAUGE OR PIEZO-RESISTIVE GAUGES
Selection and installation factors for bonded metallic strain gauges
(Factors influencing metallic gauge characteristics and application)

1. Grid material & construction.
2. Backing material
3. Bonding material
4. Gauge protection.
5. Gauge configuration
STRAIN GAUGE BRIDGE CIRCUIT FOR STRAIN MEASUREMENT

1) balanced (null) condition: how to measure strain
QUARTER BRIDGE
(finding strain using one strain gauge)
b. Half bridge (when two gauges are used for strain measurement)
Full bridge (when four gauges are used for strain measurement)

Gauge $R_1$ and $R_4$ is under tension
Gauge $R_2$ and $R_3$ is under compression
STRAIN GAUGE TORSION METER
MULTIPLE-GRID ROSSETTS

Two Element Rosette

Three Element Rosette (Rectangular)

Three Element Rosette (Delta)
MEASUREMENT OF HUMIDITY

- measurement of humidity.
- moisture content in the gases
- sling psychrometer
- absorption psychrometer
- dew point meter
Importance of humidity measurement & control

- for human comforts.
- Requirement of low humidity to prevent withering of food products and spoilage of dried eggs or dried milk.
- Requirement of low humidity to prevent dry-out and cracking of leather, mildewing of canvas and leather.
- Protection of cargoes on ships from condensation damage.
- Requisite moisture conditions for drying process.
PSYCHROMETRIC CHARTS
CLASSIFICATION OF INSTRUMENTS USED TO MEASURE MOISTURE AND HUMIDITY

1. Sling psychrometer
2. Gravimetric hygrometer
3. Absorption hygrometer
   a. Mechanical humidity sensing absorption hygrometer
   b. Electrical humidity sensing absorption hygrometer
4. Resistive hygrometers
5. Capacitive hygrometers
6. Microwave refractometer
7. Crystal hygrometer
8. Aluminum oxide hygrometer
ABSORPTION HYGROMETER
DEW POINT METER (INDUSTRIAL TYPE)
ELECTRICAL METHOD FOR MOISTURE DETERMINATION
MEASUREMENT OF FORCE, TORQUE AND POWER

ELASTIC FORCE METERS, LOAD CELLS, TORSION METERS, DYNAMOMETERS
Scales and balances: Balancing the force against a known gravitational force on standard mass.

Hydraulic and pneumatic load cells: Translating the force to fluid pressure and then measuring the resulting pressure.

Proving ring: Applying the force to some elastic member and then measuring the resulting deflection.

Applying the force to known mass and then measuring the resulting acceleration.

Balancing the force against a magnetic force developed by interaction of a magnet and current carrying coil.
1a) **Equal arm beam balance:**

![Diagram of an equal arm beam balance](image)
1b) Un-equal arm beam balance:
1c) Pendulum scale:
SCALE AND BALANCES:

Elastic force meters:
PROVING RING

- Force to be measured
- External boss
- Internal boss
- Vibrating reed
- Proving ring (or) Steel ring
- Micrometer wheel
4a. Hydraulic load cell:
4b. Pneumatic load cell:
4c. Strain gauge load cell:
METHODS OF TORQUE MEASUREMENT

1) Gravimetric method
2) Torque measurement of rotating machines
3) Mechanical torsion meter
4) Optical torsion meter
5) Electrical torsion meter
6) Strain gauge torsion meter
1) Gravimetric method:
2) Torque measurement of rotating machines
3) Mechanical torsion meter
4) Optical torsion meter:
5) Electrical torsion meter

![Diagram of Electrical Torsion Meter]
Methods of Torque measurement

6) Strain gauge torsion meter:
Classification of Dynamometers

i. Absorption dynamometers

ii. Transmission dynamometers

iii. Driving dynamometers
The device 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.

Examples of absorption dynamometers are

1a. Mechanical brakes
   a.1 block type prony brake
   a.2 band type prony brake
   a.3 rope brake

1b. Hydraulic or fluid friction brake

1c. Eddy current dynamometers
a.1. block type prony brake
Mechanical brakes

a.2: Band type prony brake:
a.3: Rope brake dynamometer:
Hydraulic or fluid friction Dynamometer
Eddy current dynamometer

- Cooling water in
- Exciting coil
- Cast iron stator
- Steel rotor
- Rotating shaft
- Anti friction bearing
- Cooling water out
ELECTRIC MOTOR-GENERATOR
DYNAMOMETER
ELEMNTS OF CONTROL SYSTEMS

- Introduction, importance, Classification-open and closed systems, Servomechanisms- Examples with block diagrams-Temperature, speed and position control systems
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.
Thermometer and the mass-spring damper system can be classified as systems.

The thermometer has the input $x = \theta$ (temperature) and the output $y = l$ (length of the mercury column in the capillary).

In the mass spring arrangement, the force and the position of the mass constitute the input $t$ and output from the system, respectively.
A THERMAL SYSTEM
CLASSIFICATION OF CONTROL SYSTEM

i) open loop system
   (Unmonitored control system)

ii) closed loop system
2. CLOSED LOOP SYSTEM

(Monitored control system)
EX.: The control of the thermal system
The closed loop systems listed above involve a continuous manual control by human operators and are classified as manual feed back or manual closed-loop systems.

Manually controlled system.
Ex.: Manually controlled thermal system.
Automatic control system: A close-loop system operating without human is called as automatic control system.

- The automatic systems are the one controlled automatically (i.e., not manually). One among the automatic control systems is the feedback controlled thermal system. In this the human operator has been replaced by an automatic controller.
Ex.: THERMAL SYSTEM: automatic feedback control
Process, Plant, 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 feedback control system.

Manipulated variable \((m)\): the quality or condition that is varies as a function of the actuating signal so as to change the value of the control element \((g_1)\).

Actuating signal \((e)\): an algebraic sum of the reference input ‘r’ and the primary feedback ‘b’. The actuating signal is also called the error or control action.
Primary feed-back signal (b): a function f 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 sign.
Disturbance (u): an undesirable variable applied to the system which tends affect adversely the value of the variable being controlled. The process disturbance may be due to changes in set point, supply, demand, environmental 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 feedback signal ‘b’.

Control element (g₁): 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’.
NEGATIVE FEEDBACK SIGNAL

Reference
Input (r)

Controller

Process

Output (c)

Error (e = r - b)

Feedback element

b

e = r - b
Reference input (r)

\[ e = r + b \]

Controller

Process

Output (c)

Feedback signal (b)

Feedback element

Error (e = r + b)
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.
POSITION CONTROL SYSTEM WITH SERVOMECHANISM:
Thank you