INSTRUMENTATION ENGINEERING

Section A

Sensors and Industrial Instrumentation

Section B

Optical Instrumentation

Comprehensive Theory
with Solved Examples *and* Practice Questions

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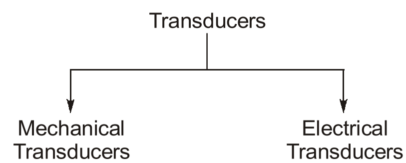
CHAPTER

1

Introduction to Transducers

Section-A

1.1 TRANSDUCERS



A transducer is a device which converts one kind of energy to the other. The conversion can be to or from electrical, electromechanical, photonic, photo-voltaic or any other form of energy. Transducers are called as the primary sensing elements. They have a vast application in the industrial measurement and control. Industry handles a large number of process which include the measurement of different process variable like flow, temperature, pressure, liquid level etc., these process variables can easily be transduced or converted in the electrical form with the help of the electrical transducers, these electrical signals which are proportional to the process variables can then be used for display and the control purposes, and the input to the transducer is termed as the information. Transducers can be of mechanical or electrical type.

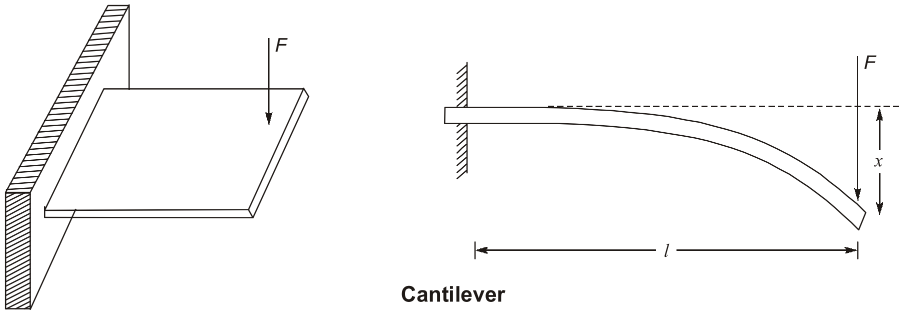
1.2 MECHANICAL TRANSDUCERS

These are the transducers which convert the mechanical quantity (e.g. force or torque) into the equivalent displacement. Some of the commonly used mechanical sensing elements are :

Spring Device

These are the mechanical transducers which convert a force or torque into displacement; These type of devices include.

Cantilever

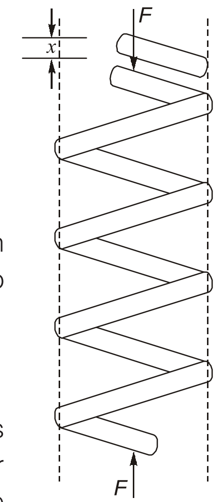


Cantilever

When a force 'F' is applied to a cantilever beam it gets bent to some displacement 'x', the value of 'x' can be easily find and is calibrated in terms of input force applied. So knowing about the displacement 'x' we can easily find the amount of force applied to the cantilever beam.

Helical Spring

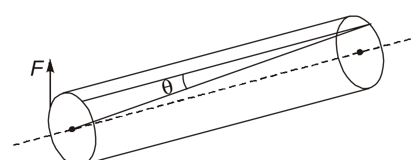
In case of Helical spring when a force 'F' is applied to both the sides of the spring then a displacement 'x' produced in the spring which is calibrated in terms of the applied force. So if we know about the displacement 'x' we can easily determine the applied force 'F'.



Helical Spring

Torsion Bars

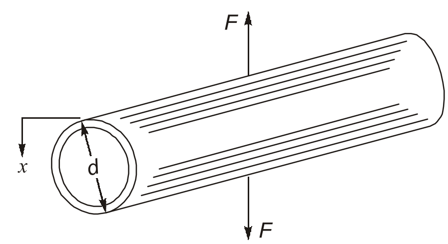
These type of transducers are used for the measurement of torque. The torsion bars are fixed to the shaft for torque measurement. When torque is produced, it produces an angular deflection/displacement into the bar, this angular displacement (θ) is proportional to the torque of the shaft.



Torsion Bar

Proving Rings

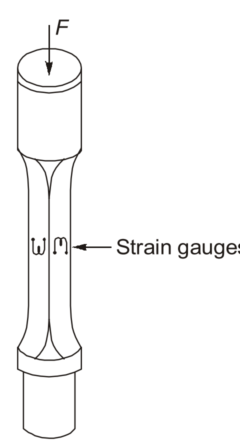
These type of transducers are used for the measurement of weight, force or load. The lateral outward force 'F' is applied to the proving ring which causes the deflection 'x' as shown in the given figure. The deflection 'x' is calibrated in terms of the force 'F' and hence can be used for the measurement of force. Proving rings are made of steel.



Proving Ring

Load Cell

Load cells are used for the measurement of force. They utilize the elastic members as the primary sensing element. The strain is produced in the load cells when an external force 'F' as shown in the figure is applied to them. This strain in then sensed with the help of strain gauges. The strain measured is proportional to the applied force.



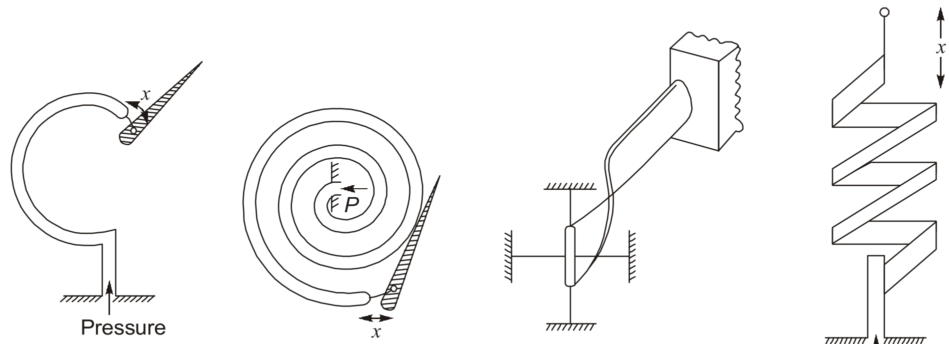
Load Cell

Pressure Sensitive Devices

Pressure sensitive devices are those devices which convert the applied pressure into the displacement. The displacement is then measured with the help of the electrical transducers. The output of the electrical transducers is proportional to the displacement and hence gives the measure of applied pressure. These can be of different types:

Bourdon Tube

Bourdon tube is a C-shaped tube which has two ends, with one end free (which is closed) and the other end kept open through which the fluid is allowed to enter. When the fluid pressure is allowed to enter the tube, the free end of the tube tries to straighten out end hence leads to the displacement of the pointer attached to it. This displacement can be amplified will the help of gear and pinion arrangement.



Bourdon tubes are preferred for high pressure measurement, as they have good accuracy at high pressure.

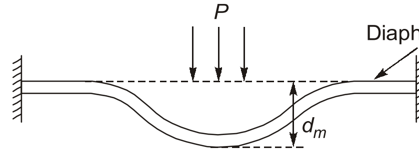
- Bourdon tubes measure gauge pressure, they are made up of brass, phosphor, bronze, beryllium copper, and steel.
- **C-type Bourdon tube have an arc of 250° and hence they are called as the C-shaped Bourdon tubes.**
- C-type Bourdon tube have low output displacement hence they need amplification which is provided by the gear and pinion arrangement, but the backlash error comes in due to pressure of gear and pinion arrangement.
- Spiral and Helical type have high output displacement and hence they do not need any gear pinion arrangement for amplification also they are free from backlash error.

Accuracy order

Spiral type > Helical type > C-type

Diaphragm

- Diaphragm are the thin circular disc which is used for the measurement of pressure. The unknown pressure is applied to one of its ends, and it tends to expand towards the opposite side. The displacement produced is proportional to the applied pressure.

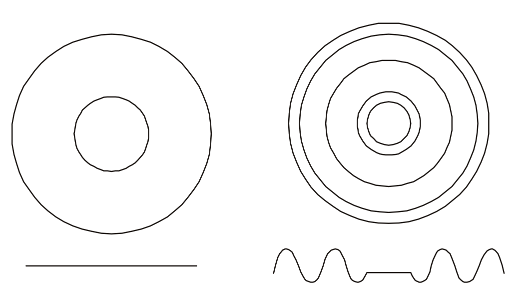


Diaphragm

- This displacement (d_m) is proportional to the applied pressure (P), hence knowing about this displacement we can easily find the pressure applied.

Diaphragm are used for low pressure measurement.

Types of Diaphragm



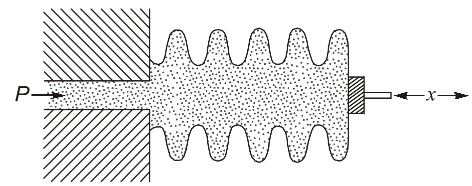
(Flat type) (Corrugated Type)

- Corrugated type diaphragm has greater surface area hence its sensitivity is higher than the flat diaphragm

Order of sensitivity:

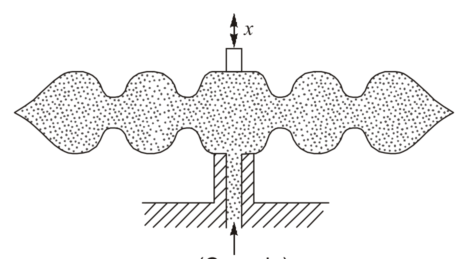
Corrugated type > Flat type

Bellows



- Bellows are the pressure sensing elements. They consists of cylindrical metal box with corrugated walls made of spring material like phosphor bronze, brass and steel. The walls are very thin with thickness of about 0.1 mm.
- As shown in the figure above, the pressure 'P' is allowed to enter from the left side of the bellows, this tends to expand the bellows to the right side (as the right end is free), but the bellows material is springly by nature and hence it puts a backward force and tries to come back and results in a displacement 'x', proportional to the applied pressure 'P'.
- If the input pressure is low then the spring material can provide sufficient backward force to control it, but if input pressure is high the displacement will go uncontrolled. Thus, **Bellows are used for low pressure measurement.**

Capsules



P (Capsule)

- Two diaphragm are joined to each other to form a capsule. Increasing the pressure into the capsule causes it to expand while decreasing its pressure causes it to contract, so the resultant displacement produced is an indication of the pressure applied.
- Since two diaphragm are attached to each other, hence the combined displacement produced is greater than that produced by the single diaphragm. Hence,

  Sensitivity of capsule > Sensitivity of diaphragm.

EXAMPLE : 1.1

A transducer converts
(a) mechanical energy into electrical energy only
(b) mechanical displacement into electrical signal only
(c) one form of energy into another form of energy only
(d) electrical energy into mechanical form only

Solution : (c)

1.3 ELECTRICAL TRANSDUCERS

- The transducers which convert the mechanical quantity into electric energy are called as the electric transducers. The mechanical quantity to be measured is first converted into displacement which is then converted to the electric energy with the help of an electrical transducers.
  - Primary Transducers

    Mechanical (pressure or force etc.) $\rightarrow$ Displacement

- Secondary Transducers
  Displacement → Electric Energy

- The electrical output may be either, current, voltage or frequency.
  Another name of transducer is pickup.

Advantages of Electrical Transducers Over Mechanical Transducers

- Mechanical transducers have frictional losses while electrical transducers are free from frictional losses.
- Electrical signals can be easily amplified while it is difficult to amplify mechanical output.
- Electrical signals can be easily transmitted from one place to another hence they have vast telemetry applications.
- Mechanical transducers have mass-inertia effects, which can be minimized by electrical transducers.
- Signal conditioning can be done with the electrical transducers output, which can be brought to a desired power level, but mechanical output cannot be signal conditioned.

Classification of Transducers

The transducers can be classified on the basis of

- Transduction form used.
- Primary and Secondary transducers.
- Active and Passive transducers.
- Digital and Analog transducers.
- Transducers and Inverse transducers.

Classification Based on Principle of Transduction

- On the basis of principle of transduction used they can be classified as resistive, inductive or capacitive transducers, the transduction depends on how they transduce the input quantity into the resistance, capacitance or inductance which can be measured by bridge or any other electronic circuitry.

Electrical Parameter and Class of Transducer	Principle of Operation and Nature of Device	Typical Application
	Passive Transducers (externally powered)	
1. **Resistance**		
Potentiometer device	Positioning of the slider by an external force varies the resistance in a potentiometer or a bridge circuit.	Pressure, displacement
Resistance strain gauge	Resistance of a wire or semiconductor is changed by elongation or compression due to externally applied stress.	Force, torque, displacement.
Pirani gauge or hot wire meter	Resistance of a heating element is varied by convection cooling of a stream of gas.	Gas flow, gas pressure.
Resistance thermometer	Resistance of pure metal wire with wire with a large positive temperature co-efficient of resistance varies with temperature.	Temperature, radiant heat

Thermistor	Resistance of certain metal oxides with negative temperature coefficient of resistance varies with temperature.	Temperature, flow
Resistance hygrometer	Resistance of a conductive strip changes with moisture content.	Relative humidity
Photoconductive cell	Resistance of the cell as a circuit element varies with incident light.	Photosensitive relay.
2. **Capacitance**		
Variable capacitance pre gauge	Distance between two parallel is varied by an externally applied force.	Displacement, pressure.
Capacitor microphone	Sound pressure varies the capacitance between a fixed plate and a movable diaphragm.	Speech, music, noise
3. **Inductance**		
Magnetic circuit transducer	Self-inductance or mutual inductance of a.c. excited coil is varied by changes in the magnetic circuit.	Pressure, displacement
Reluctance pick up	Reluctance of the magnetic circuits is varied by changing the position of the iron core of coil.	Pressure, displacement, vibration, position
Differential transformer	The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force.	Pressure, force, displacement, position
Eddy current gauge	Induction of a coil is varied by the proximity of an eddy current plate.	Displacement, thickness.
Magnetostriction gauge	Magnetic properties are varied by pressure and stress.	Force, pressure, sound.
4. **Voltage and Current**		
Hall effect pickup	A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current.	Magnetic flux, current power
Tonization chamber	Electron flow induced by ionization of gas due to radioactive radiation.	Particle counting radiation.
Photoemissive cell	Electron emission due to incident radiation upon photoemissive surface.	Light and radiation.
Photomultiplier tube	Secondary electron emission due to incident radiation on photosensitive cathode.	Light & radiation, photosensitive relays.
Self-generating Transducers (No External Power)		
Thermocouple and thermopile	An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated.	Temperature, heat, flow, radiation
Moving coil generator	Motion of a coil in a magnetic field generates a voltage.	Velocity, vibrations
Piezoelectric pick-up	An emf is generated when an external force is applied to certain crystalline materials, such as quartz.	Sound, vibrations, acc., pre changes.
Photovoltaic	A voltage is generated in a semi-conductor junction device when radiant energy stimulates the cell.	Light meter, solar cell

Primary and Secondary Transducers

- The transducers which convert the physical quantity into the mechanical displacement are called as the Primary transducers. eg. Bourdon Tube converts the input pressure into the displacement hence it acts as the primary transducers.
- The transducers which convert the mechanical displacement into the electrical output are called as the Secondary transducers. eg. LVDT, they can convert the displacement into the electrical signal by transformation and hence are termed as the Secondary transducers.

Secondary transducers are followed by the Primary transducers.

Active and Passive Transducers

- Active transducers are those transducers which do not need any external power source to produce output. They produce the electrical power output themselves. eg. Piezoelectric transducers, thermocouple.
- Passive transducers are those transducers which draws power from an external source to produce their output. eg. Potentiometer.

Digital and Analog Transducers

- The transducers which convert the input quantity into an analog output (i.e. the output which is continuous with time) are called analog transducers. eg. LVDT, Strain gauge etc.
- The transducers which convert the input quantity into an output which is in the form of pulses are called as the digital transducers. eg. Shaft encoders.

Transducers and Inverse Transducers

- Transducers and inverse transducers find a wide application in the feedback control loop for a process control and in servomechanism, where we need to convert the electric quantity to mechanical in the forward loop and mechanical to electrical quantity in the feedback or the backward loop.
- Transducers in the broader sense are the device which are used to convert the mechanical quantity into the electric quantity. eg. LVDT, thermocouple etc.
- Inverse Transducers are the device which convert the electric quantity into mechanical quantity. eg. Piezoelectric crystal.

Note: Piezoelectric crystal acts as both transducer and inverse transducer.

1.4 CHARACTERISTICS OF TRANSDUCERS

Transfer Characteristics

The transfer characteristics of an instrument is a graphical representation of the relationship between the input and output of the transducer.

Transfer Function

So the transfer function is the relationship between the input and the output.

Sensitivity

Sensitivity is defined as the ratio of the change in the output to the change in the input for a small time.

$$\text{Sensitivity} = \frac{\Delta Q_0}{\Delta Q_i}$$

NOTE
- Sensitivity of a transducer is not constant but it depends on the input.
- Sensitivity of the transducers becomes constant for the linear transfer characteristics.

Scale factor

Scale factor is defined as the inverse of sensitivity.

$$\text{Scale factor} = \frac{1}{S} = \frac{\Delta Q_i}{\Delta Q_0}$$

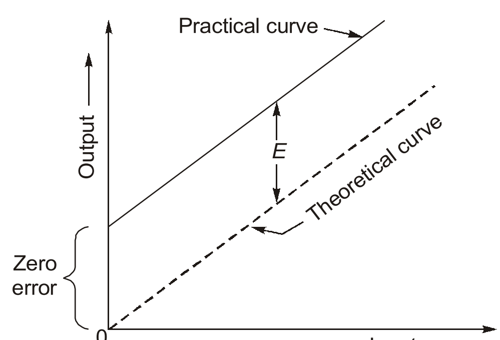
Error

Error in the transducers is said to occur when the input-output relationship deviates from the already defined input-output relationship for the transducer. Suppose, the output on account of the input (Q_i) has to be (Q_0) but practically it comes out to be (Q'_0) then the error for the transducer is given as (ε).

$$\varepsilon = Q'_0 - Q_0$$

Zero Error

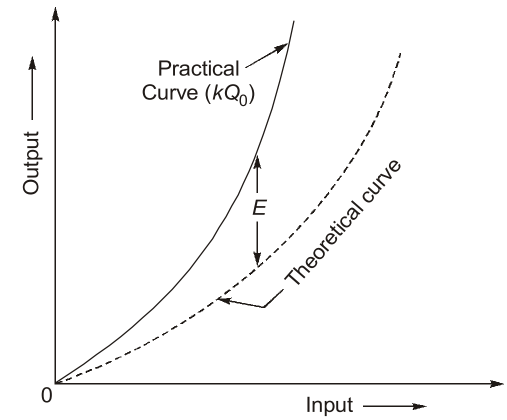
When the output deviates from the correct value of the output by a constant value over the entire range of the transducer, then the error is called as the zero error.



(Zero error)

Sensitivity Error

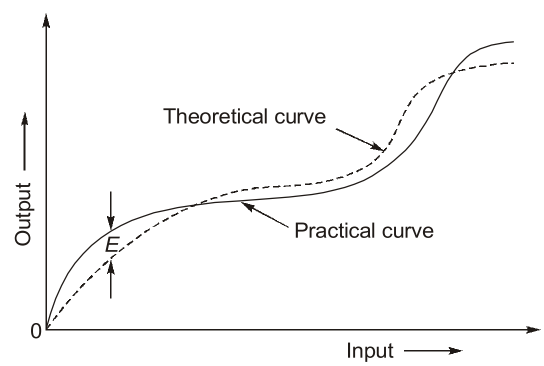
This type of error occurs when there is a proportional change all along the upward scale of the instrument. Suppose, the correct output is Q_0, the output due to error would become (KQ_0) over the entire range, where 'K' is the constant, then the error encountered is the sensitivity error as shown in the figure below:



(Sensitivity error)

Non-Conformity Error

Nonconformity errors are those errors in which the experimentally obtained transfer function is different from the theoretically obtained transfer function.



(Non-conformity error)

Hysteresis Error

When the transducer is used again and again or used more frequently, then the output of the transducer at a particular instant become sensitive to the previous values of inputs together with the input at that instant, hence we may get different outputs for same magnitude of inputs applied this is called as the hysteresis error.

EXAMPLE : 1.2

In a transducer, the experimentally obtained transfer function is different from the theoretical transfer function, the errors result from this difference are called.

(a) Zero errors
(b) Sensitivity errors
(c) Nonconformity errors
(d) Dynamic errors [GAIL-2010]

Solution : (c)

EXAMPLE : 1.3

In a transducer, the observed output deviates from the correct value by a constant factor the resulting error is called

(a) Zero error
(b) Sensitivity error
(c) Nonconformity error
(d) Hysteresis error

Solution : (b)

1.5 INPUT CHARACTERISTICS

The first and the necessary consideration is the type of input we are going to measure and also its operating range. So for the input characteristics the type and operating range should be taken into account. The input characteristics includes the input resistance of the transducer.

Loading Effects

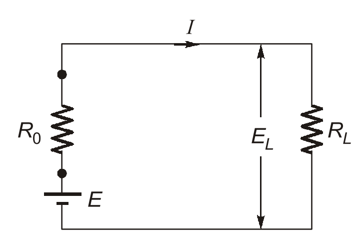
When the transducer is brought in contact with the quantity to be measured, it extracts some power or energy from it, which is called as the loading. Ideally the loading the transducer should be zero, or the measuring device must not extract any energy from the quantity to be measured.

1.6 OUTPUT CHARACTERISTICS

- Output characteristics of a transducer includes its output resistance. Ideally the output resistance of the transducer must be kept zero in order to have no-loading effects. Practically it cannot be kept zero so it must be kept minimum.

  The output characteristics determines the amount of power that can be transferred to the succeeding stages.
- Depending on the output impedance of the transducer and the input impedance of the succeeding stage, the transducer may act as a constant voltage source or a constant current source.

Case-I :



$R_0 << R_L$

$R_0 \rightarrow$ output resistance of the source.

$R_L \rightarrow$ load resistance.

$$I = \frac{E}{R_0 + R_L}$$

$$E_L = \frac{ER_L}{R_0 + R_L} = \frac{E}{1 + \frac{R_0}{R_L}}$$

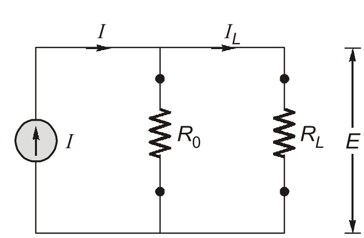
when ($R_0 << R_L$) then R_0/R_L is negligible.

$$E_L = E$$

So, if $R_0 << R_L$ then the transducer will act as a constant voltage source.

If the output impedance is low compared to the forward impedance of the system, the transducer has the characteristics of the constant voltage source.

Case-II :



$R_0 >> R_L$

$$I_L = \frac{IR_0}{R_0 + R_L} = \frac{I}{1 + \frac{R_L}{R_0}}$$

when ($R_L << R_0$) the R_L/R_0 is negligible

$$I_L = I$$

So, if $R_L << R_0$ then the transducer will act as a constant current source.

If the output impedance is high, compared to the forward impedance of the system, the transducer has the characteristics of the constant current source.

EXAMPLE : 1.4

A transducer has an output impedance of 1 kΩ and a load resistance of 1 MΩ, the transducer behaves as

(a) Constant current source
(b) Constant voltage source
(c) Constant power source
(d) None of the above

[GAIL-2010]

Solution : (b)

Since, ($R_L >> R_0$), hence the transducer will behave as a constant voltage source.

EXAMPLE : 1.5

If a transducer has an output impedance of 1 kΩ and a load resistance of 1 Ω, it then behaves as

(a) Constant current source
(b) Constant voltage source
(c) Constant impedance source
(d) None of the above

Solution : (a)

Since, ($R_0 >> R_L$), hence the transducer will behave as a constant current source.

EXAMPLE : 1.6

While selecting a transducer for a particular application :

(a) only input characteristics should be considered.
(b) only output characteristics should be considered.
(c) only transfer characteristics should be considered.
(d) input, output and transfer characteristics should be considered.

Solution : (d)

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OBJECTIVE BRAIN TEASERS

Q.1 Inverse transducers
(a) converts electrical energy to any other form of energy
(b) converts electrical energy to light energy
(c) converts mechanical displacement into electrical signal
(d) converts electrical energy to mechanical form

Q.2 Which of the following is an active transducer?
(a) strain gauge
(b) selsyn
(c) photovoltaic cell
(d) photoemissive cell

Q.3 Some of the functional building blocks of a measurement system are:
Primary Sensing Element (PSE)
Variable Conversion Element (VCE), or Transducer
Data Transmission Element (DTE)
Variable Manipulation Element (VME)
Data Presentation Element (DPE)
The correct sequential connection of the functional building blocks for an electronic pressure gauge will be
(a) PSE, VME, VCE, DPE, DTE
(b) PSE, VCE, VME, DTE, DPE
(c) DTE, DPE, VCE, PSE, VME
(d) PSE, VCE, DTE, DPE, VME

Q.4 The transducers which convert the physical quantity into the mechanical displacement are called
(a) Primary transducers
(b) Secondary transducers
(c) Tertiary transducers
(d) Inverse transducers

Q.5 The transducers which convert the mechanical displacement into the electrical form are called the
(a) Primary transducers
(b) Secondary transducers
(c) Tertiary transducers
(d) Inverse transducers

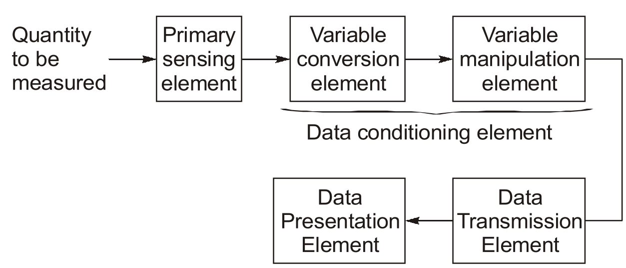
ANSWERS KEY

1. (a) 2. (c) 3. (b) 4. (a) 5. (b)

HINTS & EXPLANATIONS

3. (b)

Functional elements of a measurement system are shown below:



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