Qualities of Measurements

Chapter 1

INTRODUCTION 1.1

Instrumentation is a technology of measurement which serves not only science but all branches of engineering, medicine, and almost every human endeavour. The knowledge of any parameter largely depends on the measurement. The indepth knowledge of any parameter can be easily understood by the use of measurement, and further modifications can also be obtained.

Measuring is basically used to monitor a process or operation, or as well as the controlling process. For example, thermometers, barometers, anemometers are used to indicate the environmental conditions. Similarly, water, gas and electric meters are used to keep track of the quantity of the commodity used, and also special monitoring equipment are used in hospitals.

Whatever may be the nature of application, intelligent selection and use of measuring equipment depends on a broad knowledge of what is available and how the performance of the equipment renders itself for the job to be performed.

But there are some basic measurement techniques and devices that are useful and will continue to be widely used also. There is always a need for improvement and development of new equipment to solve measurement problems.

The major problem encountered with any measuring instrument is the error. Therefore, it is obviously necessary to select the appropriate measuring instrument and measurement method which minimises error. To avoid errors in any experimental work, careful planning, execution and evaluation of the experiment are essential.

The basic concern of any measurement is that the measuring instrument should not effect the quantity being measured; in practice, this non-interference principle is never strictly obeyed. Null measurements with the use of feedback in an instrument minimise these interference effects.

PERFORMANCE CHARACTERISTICS 1.2

A knowledge of the performance characteristics of an instrument is essential for selecting the most suitable instrument for specific measuring jobs. It consists of two basic characteristics—static and dynamic.

STATIC CHARACTERISTICS 1.3

The static characteristics of an instrument are, in general, considered for instruments which are used to measure an unvarying process condition. All the static performance characteristics are obtained by one form or another of a process called calibration. There are a number of related definitions (or characteristics), which are described below, such as accuracy, precision, repeatability, resolution, errors, sensitivity, etc.

1. ***Instrument*** A device or mechanism used to determine the present value of the quantity under measurement.
2. ***Measurement*** The process of determining the amount, degree, or capacity by comparison (direct or indirect) with the accepted standards of the system units being used.
3. ***Accuracy*** The degree of exactness (closeness) of a measurement compared to the expected (desired) value.
4. ***Resolution*** The smallest change in a measured variable to which an instrument will respond.
5. ***Precision*** A measure of the consistency or repeatability of measurements, i.e. successive reading do not differ. (Precision is the consistency of the instrument output for a given value of input).
6. ***Expected value*** The design value, i.e. the most probable value that calculations indicate one should expect to measure.
7. ***Error*** The deviation of the true value from the desired value.
8. ***Sensitivity*** The ratio of the change in output (response) of the instrument to a change of input or measured variable.

ERROR IN MEASUREMENT 1.4

Measurement is the process of comparing an unknown quantity with an accepted standard quantity. It involves connecting a measuring instrument into the system under consideration and observing the resulting response on the instrument. The measurement thus obtained is a quantitative measure of the so-called "true value" (since it is very difficult to define the true value, the term "expected value" is used). Any measurement is affected by many variables, therefore the results rarely reflect the expected value. For example, connecting a measuring instrument into the circuit under consideration always disturbs (changes) the circuit, causing the measurement to differ from the expected value.

Some factors that affect the measurements are related to the measuring instruments themselves. Other factors are related to the person using the instrument. The degree to which a measurement nears the expected value is expressed in terms of the error of measurement.

Error may be expressed either as absolute or as percentage of error.

Absolute error may be defined as the difference between the expected value of the variable and the measured value of the variable, or

$$e = Y_n - X_n$$

where e = absolute error
Y_n = expected value
X_n = measured value

Therefore $$\%\ \text{Error} = \frac{\text{Absolute value}}{\text{Expected value}} \times 100 = \frac{e}{Y_n} \times 100$$

Therefore $$\%\ \text{Error} = \left(\frac{Y_n - X_n}{Y_n}\right) \times 100$$

It is more frequently expressed as a accuracy rather than error.

Therefore $$A = 1 - \left|\frac{Y_n - X_n}{Y_n}\right|$$

where A is the relative accuracy.
Accuracy is expressed as % accuracy

$$a = 100\% - \%\ \text{error}$$

$$a = A \times 100\ \%$$

where a is the % accuracy.

Example 1.1 (a) *The expected value of the voltage across a resistor is 80 V. However, the measurement gives a value of 79 V. Calculate (i) absolute error, (ii) % error, (iii) relative accuracy, and (iv) % of accuracy.*

Solution

(i) Absolute error $e = Y_n - X_n = 80 - 79 = 1$ V

(ii) $\%\ \text{Error} = \dfrac{Y_n - X_n}{Y_n} \times 100 = \dfrac{80 - 79}{80} \times 100 = 1.25\%$

(iii) Relative Accuracy

$$A = 1 - \left|\frac{Y_n - X_n}{Y_n}\right| = 1 - \left|\frac{80 - 79}{80}\right|$$

$\therefore$ $A = 1 - 1/80 = 79/80 = 0.9875$

(iv) % of Accuracy $a = 100 \times A = 100 \times 0.9875 = 98.75\%$
or $a = 100\% - \%$ of error $= 100\% - 1.25\% = 98.75\%$

Example 1.1 (b) *The expected value of the current through a resistor is 20 mA. However the measurement yields a current value of 18 mA. Calculate (i) absolute error (ii) % error (iii) relative accuracy (iv) % accuracy*

Solution

Step 1: Absolute error

$$e = Y_n - X_n$$

where e = error, Y_n = expected value, X_n = measured value

Given $Y_n = 20$ mA and $X_n = 18$ mA
Therefore $e = Y_n - X_n = 20$ mA $-$ 18 mA $= 2$ mA

Step 2: % error

$$\% \text{ error} = \frac{Y_n - X_n}{Y_n} \times 100 = \frac{20 \text{ mA} - 18 \text{ mA}}{20 \text{ mA}} \times 100 = \frac{2 \text{ mA}}{20 \text{ mA}} \times 100 = 10\%$$

Step 3: Relative accuracy

$$A = 1 - \left|\frac{Y_n - X_n}{Y_n}\right| = 1 - \left|\frac{20 \text{ mA} - 18 \text{ mA}}{20 \text{ mA}}\right| = 1 - \frac{2}{20} = 1 - 0.1 = 0.90$$

Step 4: % accuracy

$$a = 100\% - \%\text{error} = 100\% - 10\% = 90\%$$

and
$$a = A \times 100\% = 0.90 \times 100\% = 90\%$$

If a measurement is accurate, it must also be precise, i.e. Accuracy means precision. However, a precision measurement may not be accurate. (The precision of a measurement is a quantitative or numerical indication of the closeness with which a repeated set of measurement of the same variable agree with the average set of measurements.) Precision can also be expressed mathematically as

$$P = 1 - \left|\frac{X_n - \bar{X}_n}{\bar{X}_n}\right|$$

where X_n = value of the nth measurement
$\bar{X}_n$ = average set of measurement

Example 1.2 *Table 1.1 gives the set of 10 measurement that were recorded in the laboratory. Calculate the precision of the 6th measurement.*

Table 1.1

Measurement number	*Measurement value X_n*
1	98
2	101
3	102
4	97
5	101
6	100
7	103
8	98
9	106
10	99

Solution The average value for the set of measurements is given by

$$\overline{X}_n = \frac{\text{Sum of the 10 measurement values}}{10}$$

$$= \frac{1005}{10} = 100.5$$

$$\text{Precision} = 1 - \left| \frac{X_n - \overline{X}_n}{\overline{X}_n} \right|$$

For the 6th reading

$$\text{Precision} = 1 - \left| \frac{100 - 100.5}{100.5} \right| = 1 - \frac{0.5}{100.5} = \frac{100}{100.5} = 0.995$$

The accuracy and precision of measurements depend not only on the quality of the measuring instrument but also on the person using it. However, whatever the quality of the instrument and the case exercised by the user, there is always some error present in the measurement of physical quantities.

TYPES OF STATIC ERROR 1.5

The static error of a measuring instrument is the numerical difference between the true value of a quantity and its value as obtained by measurement, i.e. repeated measurement of the same quantity gives different indications. Static errors are categorised as gross errors or human errors, systematic errors, and random errors.

1.5.1 Gross Errors

These errors are mainly due to human mistakes in reading or in using instruments or errors in recording observations. Errors may also occur due to incorrect adjustment of instruments and computational mistakes. These errors cannot be treated mathematically.

The complete elimination of gross errors is not possible, but one can minimise them. Some errors are easily detected while others may be elusive.

One of the basic gross errors that occurs frequently is the improper use of an instrument. The error can be minimized by taking proper care in reading and recording the measurement parameter.

In general, indicating instruments change ambient conditions to some extent when connected into a complete circuit. (Refer Examples 1.3(a) and (b)).

(One should therefore not be completely dependent on one reading only; at least three separate readings should be taken, preferably under conditions in which instruments are switched off and on.)

1.5.2 Systematic Errors

These errors occur due to shortcomings of the instrument, such as defective or worn parts, or ageing or effects of the environment on the instrument.

These errors are sometimes referred to as bias, and they influence all measurements of a quantity alike. A constant uniform deviation of the operation of an instrument is known as a systematic error. There are basically three types of systematic errors—(i) Instrumental, (ii) Environmental, and (iii) Observational.

(i) Instrumental Errors

Instrumental errors are inherent in measuring instruments, because of their mechanical structure. For example, in the D'Arsonval movement, friction in the bearings of various moving components, irregular spring tensions, stretching of the spring, or reduction in tension due to improper handling or overloading of the instrument.

Instrumental errors can be avoided by

(a) selecting a suitable instrument for the particular measurement applications. (Refer Examples 1.3 (a) and (b)).
(b) applying correction factors after determining the amount of instrumental error.
(c) calibrating the instrument against a standard.

(ii) Environmental Errors

Environmental errors are due to conditions external to the measuring device, including conditions in the area surrounding the instrument, such as the effects of change in temperature, humidity, barometric pressure or of magnetic or electrostatic fields.

These errors can also be avoided by (i) air conditioning, (ii) hermetically sealing certain components in the instruments, and (iii) using magnetic shields.

(iii) Observational Errors

Observational errors are errors introduced by the observer. The most common error is the parallax error introduced in reading a meter scale, and the error of estimation when obtaining a reading from a meter scale.

These errors are caused by the habits of individual observers. For example, an observer may always introduce an error by consistently holding his head too far to the left while reading a needle and scale reading.

In general, systematic errors can also be subdivided into static and dynamic errors. Static errors are caused by limitations of the measuring device or the physical laws governing its behaviour. Dynamic errors are caused by the instrument not responding fast enough to follow the changes in a measured variable.

Example 1.3 (a) *A voltmeter having a sensitivity of 1 kΩ/V is connected across an unknown resistance in series with a milliammeter reading 80 V on 150 V scale. When the milliammeter reads 10 mA, calculate the (i) Apparent resistance of the unknown resistance, (ii) Actual resistance of the unknown resistance, and (iii) Error due to the loading effect of the voltmeter.*

Solution

(i) The total circuit resistance $R_T = \dfrac{V_T}{I_T} = \dfrac{80}{10\text{ mA}} = 8\text{ k}\Omega$

(Neglecting the resistance of the milliammeter.)

(ii) The voltmeter resistance equals $R_v = 1000\ \Omega/\text{V} \times 150 = 150\text{ k}\Omega$

$\therefore$ actual value of unknown resistance $R_x = \dfrac{R_T \times R_v}{R_v - R_T} = \dfrac{8\text{k} \times 150\text{k}}{150\text{k} - 8\text{k}}$

$$= \frac{1200\text{k}^2}{142\text{k}} = 8.45\ \Omega$$

(iii) % error $= \dfrac{\text{Actual value} - \text{Apparent value}}{\text{Actual value}} = \dfrac{8.45\text{k} - 8\text{k}}{8.45\text{k}} \times 100$

$= 0.053 \times 100 = 5.3\%$

Example 1.3 (b) *Referring to Ex. 1.3 (a), if the milliammeter reads 600 mA and the voltmeter reads 30 V on a 150 V scale, calculate the following: (i) Apparent, resistance of the unknown resistance. (ii) Actual resistance of the unknown resistance. (iii) Error due to loading effect of the voltmeter.*

Comment on the loading effect due to the voltmeter for both Examples 1.3 (a) and (b). (Voltmeter sensitivity given 1000 Ω/V.)

Solution

1. The total circuit resistance is given by

$$R_T = \frac{V_T}{I_T} = \frac{30}{0.6} = 50\ \Omega$$

2. The voltmeter resistance R_v equals

$$R_v = 1000\ \Omega/\text{V} \times 150 = 150\text{ k}\Omega$$

Neglecting the resistance of the milliammeter, the value of unknown resistance = 50 Ω

$$R_x = \frac{R_T \times R_v}{R_v - R_T} = \frac{50 \times 150\text{ k}}{150\text{ k} - 50} = \frac{7500\text{ k}}{149.5\text{ k}} = 50.167\ \Omega$$

$$\%\ \text{Error} = \frac{50.167 - 50}{50.167} \times 100 = \frac{0.167}{50.167} \times 100 = 0.33\%$$

In Example 1.3 (a), a well calibrated voltmeter may give a misleading resistance when connected across two points in a high resistance circuit. The same voltmeter, when connected in a low resistance circuit (Example 1.3 (b)) may give a more dependable reading. This show that voltmeters have a loading effect in the circuit during measurement.

1.5.3 Random Errors

These are errors that remain after gross and systematic errors have been substantially reduced or at least accounted for. Random errors are generally an accumulation of a large number of small effects and may be of real concern only in measurements requiring a high degree of accuracy. Such errors can be analyzed statistically.

These errors are due to unknown causes, not determinable in the ordinary process of making measurements. Such errors are normally small and follow the laws of probability. Random errors can thus be treated mathematically.

For example, suppose a voltage is being monitored by a voltmeter which is read at 15 minutes intervals. Although the instrument operates under ideal environmental conditions and is accurately calibrated before measurement, it still gives readings that vary slightly over the period of observation. This variation cannot be corrected by any method of calibration or any other known method of control.

SOURCES OF ERROR 1.6

The sources of error, other than the inability of a piece of hardware to provide a true measurement, are as follows:

1. Insufficient knowledge of process parameters and design conditions
2. Poor design
3. Change in process parameters, irregularities, upsets, etc.
4. Poor maintenance
5. Errors caused by person operating the instrument or equipment
6. Certain design limitations

DYNAMIC CHARACTERISTICS 1.7

Instruments rarely respond instantaneously to changes in the measured variables. Instead, they exhibit slowness or sluggishness due to such things as mass, thermal capacitance, fluid capacitance or electric capacitance. In addition to this, pure delay in time is often encountered where the instrument waits for some reaction to take place. Such industrial instruments are nearly always used for measuring quantities that fluctuate with time. Therefore, the dynamic and transient behaviour of the instrument is as important as the static behaviour.

The dynamic behaviour of an instrument is determined by subjecting its primary element (sensing element) to some unknown and predetermined variations in the measured quantity. The three most common variations in the measured quantity are as follows:

1. *Step* change, in which the primary element is subjected to an instantaneous and finite change in measured variable.
2. *Linear* change, in which the primary element is following a measured variable, changing linearly with time.

3. *Sinusoidal* change, in which the primary element follows a measured variable, the magnitude of which changes in accordance with a sinusoidal function of constant amplitude.

The dynamic characteristics of an instrument are (i) speed of response, (ii) fidelity, (iii) lag, and (iv) dynamic error.

(i) *Speed of Response* It is the rapidity with which an instrument responds to changes in the measured quantity.

(ii) *Fidelity* It is the degree to which an instrument indicates the changes in the measured variable without dynamic error (faithful reproduction).

(iii) *Lag* It is the retardation or delay in the response of an instrument to changes in the measured variable.

(iv) *Dynamic Error* It is the difference between the true value of a quantity changing with time and the value indicated by the instrument, if no static error is assumed.

When measurement problems are concerned with rapidly varying quantities, the dynamic relations between the instruments input and output are generally defined by the use of differential equations.

1.7.1 Dynamic Response of Zero Order Instruments

We would like an equation that describes the performance of the zero order instrument exactly. The relations between any input and output can, by using suitable simplifying assumptions, be written as

$$a_n \frac{d^n x_o}{dt^n} + a_{n-1} \frac{d^{n-1} x_o}{dt^{n-1}} + \cdots + a_1 \frac{dx_o}{dt} + a_0 x_o$$

$$= b_m \frac{d^m x_i}{dt^m} + \cdots + b_{m-1} \frac{d^{m-1} x_i}{dt^{m-1}} + \cdots + b_1 \frac{dx_i}{dt} + b_0 \simeq x_i \quad (1.1)$$

where x_o = output quantity
x_i = input quantity
t = time

a's and b's are combinations of systems physical parameters, assumed constant.

When all the a's and b's, other than a_0 and b_0 are assumed to be zero, the differential equation degenerates into the simple equation given as

$$a_0 x_o = b_0 x_i \quad (1.2)$$

Any instrument that closely obeys Eq. (1.2) over its intended range of operating conditions is defined as a zero-order instrument. The static sensitivity (or steady state gain) of a zero-order instrument may be defined as follows

$$x_o = \frac{b_0}{a_0} x_i = K.x_i$$

where $K = b_0/a_0$ = static sensitivity

Since the equation $x_o = K\, x_i$ is an algebraic equation, it is clear that no matter how x_i might vary with time, the instrument output (reading) follows it perfectly with no distortion or time lag of any sort. Thus, a zero-order instrument represents ideal or perfect dynamic performance. A practical example of a zero order instrument is the displacement measuring potentiometer.

1.7.2 Dynamic Response of a First Order Instrument

If in Eq. (1.1) all a's and b's other than a_1, a_0, b_0 are taken as zero, we get

$$a_1 \frac{dx_o}{dt} + a_0 x_o = b_0 x_i$$

Any instrument that follows this equation is called a first order instrument. By dividing by a_0, the equation can be written as

$$\frac{a_1}{a_0}\frac{dx_o}{dt} + x_o = \frac{b_0}{a_0} x_i$$

or $$(\tau \cdot D + 1) \cdot x_o = K\, x_i$$

where $\tau = a_1/a_0$ = time constant

$K = b_0/a_0$ = static sensitivity

The time constant τ always has the dimensions of time while the static sensitivity K has the dimensions of output/input. The operational transfer function of any first order instrument is

$$\frac{x_o}{x_i} = \frac{K}{\tau D + 1}$$

A very common example of a first-order instrument is a mercury-in-glass thermometer.

1.7.3 Dynamic Response of Second Order Instrument

A second order instrument is defined as one that follows the equation

$$a_2 \frac{d^2 x_o}{dt^2} + a_1 \frac{dx_o}{dt} + a_0 x_o = b_0 x_i$$

The above equations can be reduced as

$$\left(\frac{D^2}{\omega_n^2} + \frac{2\xi D}{\omega_n} + 1\right) \cdot x_o = K x_i$$

where $\omega_n = \sqrt{\dfrac{a_0}{a_2}}$ = undamped natural frequency in radians/time

$2\xi = a_1/\sqrt{a_0\, a_2}$ = damping ratio

$K = b_0/a_0$ = static sensitivity

Transducers

Chapter 13

INTRODUCTION 13.1

A transducer is defined as a device that receives energy from one system and transmits it to another, often in a different form.

Broadly defined, the transducer is a device capable of being actuated by an energising input from one or more transmission media and in turn generating a related signal to one or more transmission systems. It provides a usable output in response to a specified input measurand, which may be a physical or mechanical quantity, property, or conditions. The energy transmitted by these systems may be electrical, mechanical or acoustical.

The nature of electrical output from the transducer depends on the basic principle involved in the design. The output may be analog, digital or frequency modulated.

Basically, there are two types of transducers, electrical, and mechanical.

ELECTRICAL TRANSDUCER 13.2

An electrical transducer is a sensing device by which the physical, mechanical or optical quantity to be measured is transformed directly by a suitable mechanism into an electrical voltage/current proportional to the input measurand.

An electrical transducer must have the following parameters:

1. ***Linearity*** The relationship between a physical parameter and the resulting electrical signal must be linear.
2. ***Sensitivity*** This is defined as the electrical output per unit change in the physical parameter (for example V/°C for a temperature sensor). High sensitivity is generally desirable for a transducer.
3. ***Dynamic Range*** The operating range of the transducer should be wide, to permit its use under a wide range of measurement conditions.
4. ***Repeatability*** The input/output relationship for a transducer should be predictable over a long period of time. This ensures reliability of operation.
5. ***Physical Size*** The transducer must have minimal weight and volume, so that its presence in the measurement system does not disturb the existing conditions.

Advantages of Electrical Transducers The main advantages of electrical transducers (conversion of physical quantity into electrical quantities) are as follows:

1. Electrical amplification and attenuation can be easily done.
2. Mass-inertia effects are minimised.
3. Effects of friction are minimised.
4. The output can be indicated and recorded remotely at a distance from the sensing medium.
5. The output can be modified to meet the requirements of the indicating or controlling units. The signal magnitude can be related in terms of the voltage current. (The analog signal information can be converted in to pulse or frequency information. Since output can be modified, modulated or amplified at will, the output signal can be easily used for recording on any suitable multichannel recording device.)
6. The signal can be conditioned or mixed to obtain any combination with outputs of similar transducers or control signals.
7. The electrical or electronic system can be controlled with a very small power level.
8. The electrical output can be easily used, transmitted and processed for the purpose of measurement.

Electrical transducers can be broadly classified into two major categories, (i) Active, (ii) Passive.

An **active transducer** generates an electrical signal directly in response to the physical parameter and does not require an external power source for its operation. Active transducers are self generating devices, which operate under energy conversion principle and generate an equivalent output signal (for example from pressure to charge or temperature to electrical potential).

Typical example of active transducers are piezo electric sensors (for generation of charge corresponding to pressure) and photo voltaic cells (for generation of voltage in response to illumination).

Passive transducers operate under energy controlling principles, which makes it necessary to use an external electrical source with them. They depend upon the change in an electrical parameter (R, L and C).

Typical example are strain gauges (for resistance change in response to pressure), and thermistors (for resistance change corresponding to temperature variations).

Electrical transducers are used mostly to measure non-electrical quantities. For this purpose a detector or sensing element is used, which converts the physical quantity into a displacement. This displacement actuates an electric transducer, which acts as a secondary transducer and give an output that is electrical in nature. This electrical quantity is measured by the standard method used for electrical measurement. The electrical signals may be current, voltage, or frequency; their production is based on R, L and C effects.

A transducer which converts a non-electrical quantity into an analog electrical signal may be considered as consisting of two parts, the sensing element, and the transduction element.

The sensing or detector element is that part of a transducer which responds to a physical phenomenon or to a change in a physical phenomenon. The response of the sensing element must be closely related to the physical phenomenon.

The transduction element transforms the output of a sensing element to an electrical output. This, in a way, acts as a secondary transducer.

Transducers may be further classified into different categories depending upon the principle employed by their transduction elements to convert physical phenomena into output electrical signals.

The different electrical phenomena employed in the transduction elements of transducers are as follows.

1. Resistive
2. Inductive
3. Capacitive
4. Electro magnetic
5. Piezo-electric
6. Photo-emissive
7. Photo-resistive
8. Potentiometric
9. Thermo-electric
10. Frequency generating

SELECTING A TRANSDUCER 13.3

The transducer or sensor has to be physically compatible with its intended application. The following should be considered while selecting a transducer.

1. ***Operating range*** Chosen to maintain range requirements and good resolution.
2. ***Sensitivity*** Chosen to allow sufficient output.
3. ***Frequency response and resonant frequency*** Flat over the entire desired range.
4. ***Environmental compatibility*** Temperature range, corrosive fluids, pressure, shocks, interaction, size and mounting restrictions.
5. ***Minimum sensitivity*** To expected stimulus, other than the measurand.
6. ***Accuracy*** Repeatability and calibration errors as well as errors expected due to sensitivity to other stimuli.
7. ***Usage and ruggedness*** Ruggedness, both of mechanical and electrical intensities versus size and weight.
8. ***Electrical parameters*** Length and type of cable required, signal to noise ratio when combined with amplifiers, and frequency response limitations.

RESISTIVE TRANSDUCER 13.4

Resistive transducers are those in which the resistance changes due to a change in some physical phenomenon. The change in the value of the resistance with a change in the length of the conductor can be used to measure displacement.

Strain gauges work on the principle that the resistance of a conductor or semiconductor changes when strained. This can be used for the measurement of displacement, force and pressure.

The resistivity of materials changes with changes in temperature. This property can be used for the measurement of temperature.

13.4.1 Potentiometer

A resistive potentiometer (pot) consists of a resistance element provided with a sliding contact, called a wiper. The motion of the sliding contact may be translatory or rotational. Some have a combination of both, with resistive elements in the form of a helix, as shown in Fig. 13.1(c). They are known as helipots.

Translatory resistive elements, as shown in Fig. 13.1(a), are linear (straight) devices. Rotational resistive devices are circular and are used for the measurement of angular displacement, as shown in Fig. 13.1(b).

Helical resistive elements are multi turn rotational devices which can be used for the measurement of either translatory or rotational motion. A potentiometer is a passive transducer since it requires an external power source for its operation.

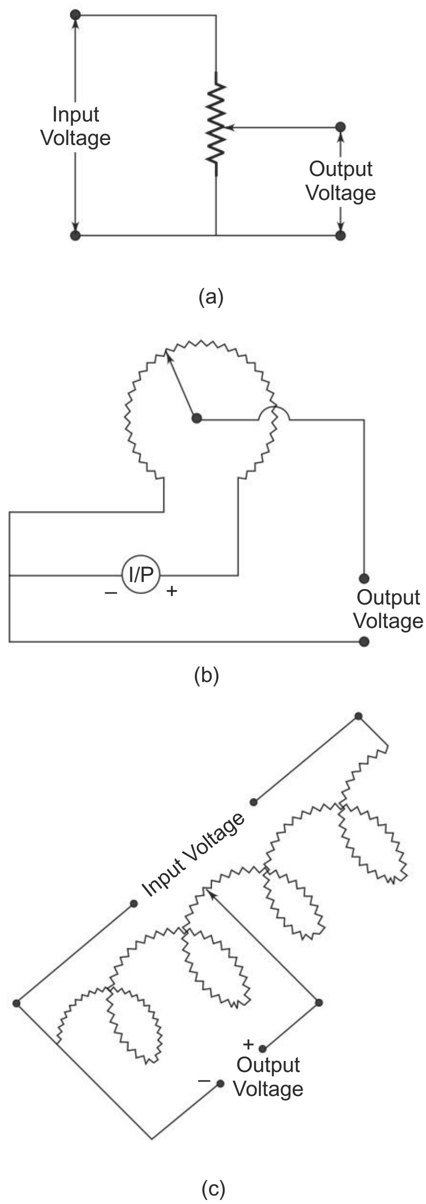


Fig. 13.1 (a) Translatory Type (b) Rotational Type (c) Helipot (Rotational)

Advantage of Potentiometers

1. They are inexpensive.
2. Simple to operate and are very useful for applications where the requirements are not particularly severe.
3. They are useful for the measurement of large amplitudes of displacement.
4. Electrical efficiency is very high, and they provide sufficient output to allow control operations.

Disadvantages

1. When using a linear potentiometer, a large force is required to move the sliding contacts.

2. The sliding contacts can wear out, become misaligned and generate noise.

13.4.2 Resistance Pressure Transducer

Measurement in the resistive type of transducer is based on the fact that a change in pressure results in a resistance change in the sensing elements. Resistance pressure transducers are of two main types. First, the electromechanical resistance transducer, in which a change of pressure, stress, position, displacement or other mechanical variation is applied to a variable resistor. The other resistance transducer is the strain gauge, where the stress acts directly on the resistance. It is very commonly used for stress and displacement measurement in instrumentation.

In the general case of pressure measurement, the sensitive resistance element may take other forms, depending on the mechanical arrangement on which the pressure is caused to act.

Figure 13.1(d) and (e) show two ways by which the pressure acts to influence the sensitive resistance element, i.e. by which pressure varies the resistance element. They are the bellow type, and the diaphragm type. (Yet another is the Bourdon tube of pressure gauge).

In each of these cases, the element moved by the pressure change is made to cause a change in resistance. This resistance change can be made part of a bridge circuit and then taken as either ac or dc output signal to determine the pressure indication.

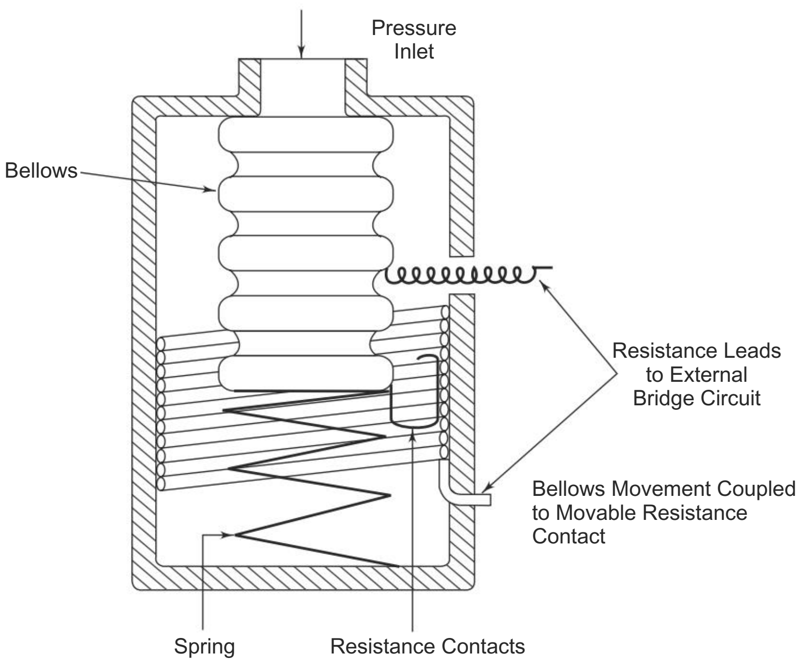


Fig. 13.1(d) Resistance pressure transducer

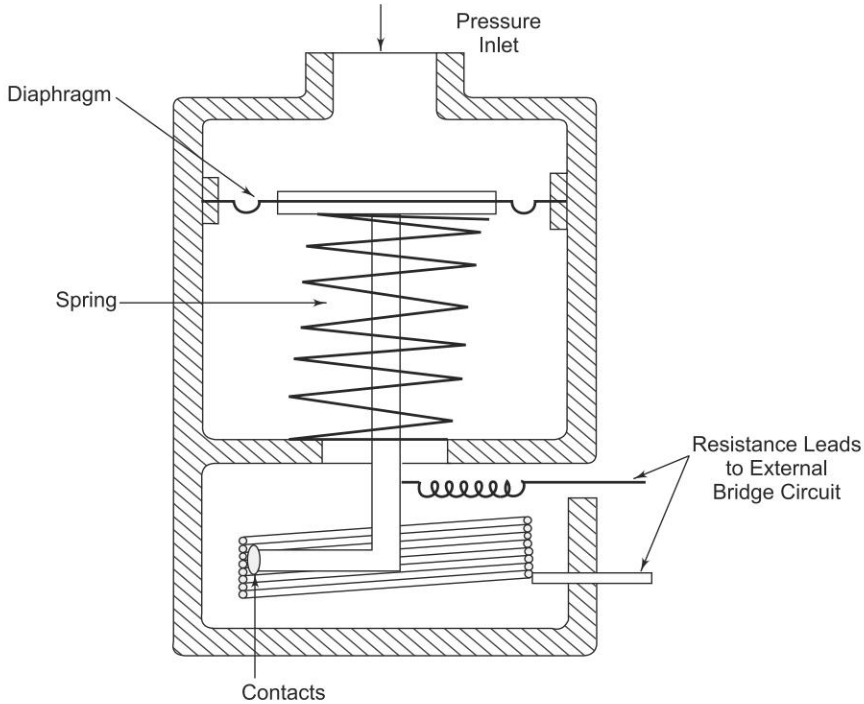


Fig. 13.1(e) Sensitive diaphragm moves the resistance contact

RESISTIVE POSITION TRANSDUCER 13.5

The principle of the resistive transducer is that the physical variable under measurement causes a resistance change in the sensing element. (A common requirement in industrial measurement and control work is to be able to sense the position of an object, or the distance it has moved).

One type of displacement transducer uses a resistive element with a sliding contact or wiper linked to the object being monitored or measured. Thus the resistance between the slider and one end of the resistance element depends on the position of the object. Figure 13.2(a) gives the construction of this type of transducer.

Figure 13.2(b) shows a typical method of use. The output voltage depends on the wiper position and is therefore a function of the shaft position. This voltage may be applied to a voltmeter calibrated in cms for visual display.

(Typical commercial units provide a choice of maximum shaft strokes, from an inch or less to 5 ft or more.) Deviation from linearity of the resistance versus distance specifications can be as low as 0.1 – 1.0%.

Considering Fig. 13.2(b), if the circuit is unloaded, the output voltage V_o is a certain fraction of V_t, depending upon the position of the wiper.

Example 13.2 *A resistive transducer with a resistance of 5 kΩ and a shaft stroke of 3.0 in. is used in the arrangement in Fig. Ex. 13.1. Potentiometer R_3–R_4 is also 5 k and V_t is 5.0 V. The initial position to be used as a reference point is such that $R_1 = R_2$ (i.e. the shaft is at the centre). At the start of the test, potentiometer R_3–R_4 is adjusted so that the bridge is balanced ($V_e = 0$). Assuming that the object being monitored moves a maximum resistance of 0.5 in. towards A, what will be the new value of V_c? (Shaft distance is 5 in.)*

Solution If the wiper moves 0.5 in. towards A from the centre, it will have moved 3 in. from *B*.

$$R_2 = \frac{3.0}{5.0} \times 5\text{ k} = 3\text{ k}\Omega$$

$$V_e = VR_2 - VR_4 = \left(\frac{R_2}{R_1 + R_2}\right) \times V_t - \left(\frac{R_4}{R_3 + R_4}\right) \times V_t$$

$$= \left(\frac{3\text{ k}}{5\text{ k}}\right) \times 5\ V - \left(\frac{2.5\text{ k}}{5\text{ k}}\right) \times 5\ V$$

$$= 3\ V - 2.5\ V = 0.5\ V$$

STRAIN GAUGES 13.6

The strain gauge is an example of a passive transducer that uses the variation in electrical resistance in wires to sense the strain produced by a force on the wires.

It is well known that stress (force/unit area) and strain (elongation or compression/unit length) in a member or portion of any object under pressure is directly related to the modulus of elasticity.

Since strain can be measured more easily by using variable resistance transducers, it is a common practice to measure strain instead of stress, to serve as an index of pressure. Such transducers are popularly known as strain gauges.

If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both the length and diameter of the conductor changes. Also, there is a change in the value of the resistivity of the conductor when subjected to strain, a property called the *piezo-resistive effect*. Therefore, resistance strain gauges are also known as *piezo resistive gauges*.

Many detectors and transducers, e.g. load cells, torque meters, pressure gauges, temperature sensors, etc. employ strain gauges as secondary transducers.

When a gauge is subjected to a positive stress, its length increases while its area of cross-section decreases. Since the resistance of a conductor is directly proportional to its length and inversely proportional to its area of cross-section, the resistance of the gauge increases with positive strain. The change in resistance value of a conductor under strain is more than for an increase in resistance due to its dimensional changes. This property is called the piezo-resistive effect.

The following types of strain gauges are the most important.

1. Wire strain gauges
2. Foil strain gauges
3. Semiconductor strain gauges

13.6.1 Resistance Wire Gauge

Resistance wire gauges are used in two basic forms, the unbonded type, and the bonded type.

1. Unbonded Resistance Wire Strain Gauge An unbonded strain gauge consists of a wire streched between two points in an insulating medium, such as air. The diameter of the wire used is about 25 μm. The wires are kept under tension so that there is no sag and no free vibration. Unbonded strain gauges are usually connected in a bridge circuit. The bridge is balanced with no load applied as shown in Fig. 13.3.

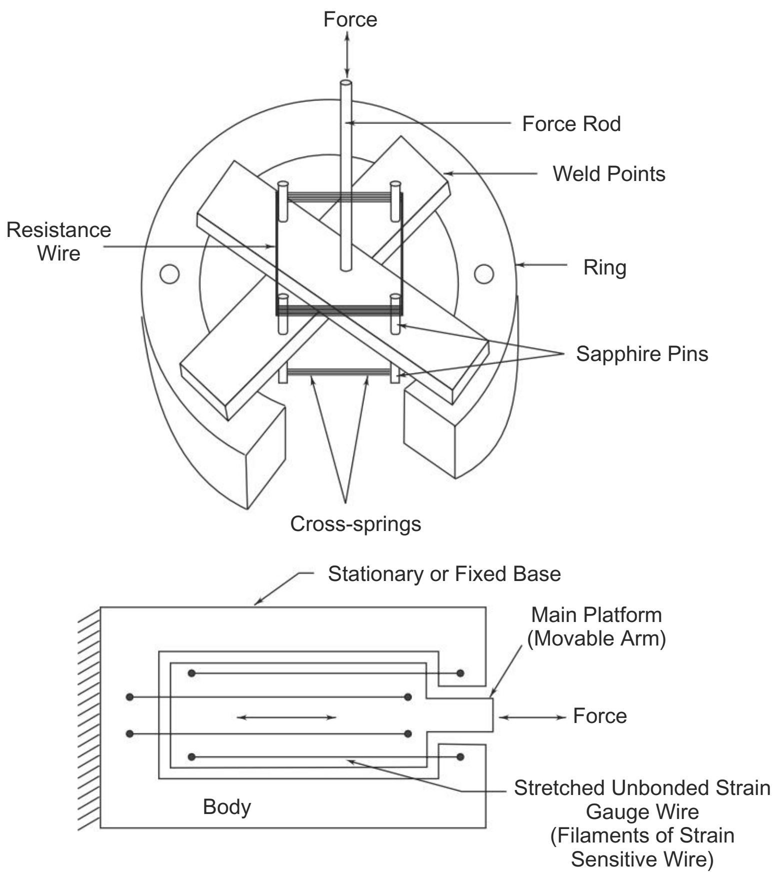


Fig. 13.3 Unbonded strain gauge

When an external load is applied, the resistance of the strain gauge changes, causing an unbalance of the bridge circuit resulting in an output voltage. This voltage is proportional to the strain. A displacement of the order of 50 μm can be detected with these strain gauges.

2. Bonded Resistance Wire Strain Gauges A metallic bonded strain gauge is shown in Fig. 13.4.

A fine wire element about 25 μm (0.025 in.) or less in diameter is looped back and forth on a carrier (base) or mounting plate, which is usually cemented to the member undergoing stress. The grid of fine wire is cemented on a carrier which may be a thin sheet of paper, bakelite, or teflon. The wire is covered on the top with a thin material, so that it is not damaged mechanically. The spreading of the wire permits uniform distribution of stress. The carrier is then bonded or cemented to the member being studied. This permits a good transfer of strain from carrier to wire.

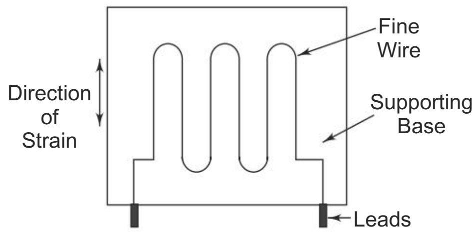


Fig. 13.4 Bonded resistance wire strain gauge

A tensile stress tends to elongate the wire and thereby increase its length and decrease its cross-sectional area. The combined effect is an increase in resistance, as seen from the following equation

$$R = \frac{\rho \times l}{A}$$

where ρ = the specific resistance of the material in Ωm
l = the length of the conductor in m
A = the area of the conductor in m^2

As a result of strain, two physical parameters are of particular interest.

1. The change in gauge resistance.
2. The change in length.

The measurement of the sensitivity of a material to strain is called the gauge factor (GF). It is the ratio of the change in resistance $\Delta R/R$ to the change in the length $\Delta l/l$

i.e.
$$\text{GF}\,(K) = \frac{\Delta R/R}{\Delta l/l} \tag{13.1}$$

where K = gauge factor
ΔR = the change in the initial resistance in Ω's
R = the initial resistance in Ω (without strain)
Δl = the change in the length in m
l = the initial length in m (without strain)

Since strain is defined as the change in length divided by the original length, i.e. $$\sigma = \frac{\Delta l}{l}$$

Eq. (13.1) can be written as

$$K = \frac{\Delta R/R}{\sigma} \tag{13.2}$$

where σ is the strain in the lateral direction.

The resistance of a conductor of uniform cross-section is

$$R = \rho \frac{\text{length}}{\text{area}}$$

$$R = \rho \frac{l}{\pi r^2}$$

Since $$r = \frac{d}{2} \quad \therefore \quad r^2 = \frac{d^2}{4}$$

$$\therefore \quad R = \rho \frac{l}{\pi\, d^2/4} = \rho \frac{l}{\pi/4\, d^2} \tag{13.3}$$

where ρ = specific resistance of the conductor
l = length of conductor
d = diameter of conductor

When the conductor is stressed, due to the strain, the length of the conductor increases by Δl and the simultaneously decreases by Δd in its diameter. Hence the resistance of the conductor can now be written as

$$R_s = \rho \frac{(l+\Delta l)}{\pi/4 (d-\Delta d)^2} = \frac{\rho(l+\Delta l)}{\pi/4\, (d^2 - 2d\,\Delta d + \Delta d^2)}$$

Since Δd is small, Δd^2 can be neglected

$$\therefore \quad R_s = \frac{\rho\,(l+\Delta l)}{\pi/4\,(d^2 - 2d\,\Delta d)}$$

$$= \frac{\rho\,(l+\Delta l)}{\pi/4 d^2 \left(1 - \dfrac{2\Delta d}{d}\right)} = \frac{\rho l\,(1+\Delta l/l)}{\pi/4 d^2 \left(1 - \dfrac{2\Delta d}{d}\right)} \tag{13.4}$$

Now, Poisson's ratio μ is defined as the ratio of strain in the lateral direction to strain in the axial direction, that is,

$$\mu = \frac{\Delta d/d}{\Delta l/l} \tag{13.5}$$

$$\therefore \quad \frac{\Delta d}{d} = \mu \frac{\Delta l}{l} \tag{13.6}$$

Substituting for $\Delta d/d$ from Eq. (13.6) in Eq. (13.4), we have

$$R_s = \frac{\rho l\,(1 + \Delta l/l)}{(\pi/4)\, d^2\,(1 - 2\mu\,\Delta l/l)}$$

Rationalising, we get

$$R_s = \frac{\rho l\,(1 + \Delta l/l)}{(\pi/4)\, d^2\,(1 - 2\mu\,\Delta l/l)}\,\frac{(1 + 2\mu\,\Delta l/l)}{(1 + 2\mu\,\Delta l/l)}$$

$$\therefore \qquad R_s = \frac{\rho l}{(\pi/4)\, d^2}\left[\frac{(1 + \Delta l/l)}{(1 - 2\mu\,\Delta l/l)}\,\frac{(1 + 2\mu\,\Delta l/l)}{(1 + 2\mu\,\Delta l/l)}\right]$$

$$\therefore \qquad R_s = \frac{\rho l}{(\pi/4)\, d^2}\left[\frac{1 + 2\mu\,\Delta l/l + 2\Delta l/l + 2\mu\,\Delta l/e\,\Delta l/l}{1 - 4\mu^2\,(\Delta l/l)^2}\right]$$

$$\therefore \qquad R_s = \frac{\rho l}{(\pi/4)\, d^2}\left[\frac{1 + 2\mu\,\Delta l/l + \Delta l/l + 2\mu\,\Delta l^2/l^2}{1 - 4\mu^2\,\Delta l^2/l^2}\right]$$

Since Δl is small, we can neglect higher powers of Δl.

$$\therefore \qquad R_s = \frac{\rho l}{(\pi/4)\, d^2}\,[1 + 2\,\mu\,\Delta l/l + \Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\, d^2}\,[1 + (2\,\mu + 1)\,\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\, d^2}\,[1 + (1 + 2\,\mu)\,\Delta l/l]$$

$$\therefore \qquad R_s = \frac{\rho l}{(\pi/4)\, d^2} + \frac{\rho l}{(\pi/4)\, d^2}\,(\Delta l/l)\,(1 + 2\,\mu)$$

Since from Eq. (13.3), $R = \dfrac{\rho l}{(\pi/4)\, d^2}$

$$\therefore \qquad R_s = R + \Delta R \tag{13.7}$$

where $\Delta R = \dfrac{\rho l}{(\pi/4)\, d^2}\,(\Delta l/l)\,(1 + 2\,\mu)$

$\therefore$ The gauge factor will now be

$$K = \frac{\Delta R/R}{\Delta l/l} = \frac{(\Delta l/l)\,(1 + 2\mu)}{\Delta l/l}$$

$$= 1 + 2\,\mu$$

$$\therefore \qquad K = 1 + 2\,\mu \tag{13.8}$$

Example 13.3 *A resistance strain gauge with a gauge factor of 2 is cemented to a steel member, which is subjected to a strain of 1×10^{-6}. If the original resistance value of the gauge is 130 Ω, calculate the change in resistance.*

Solution Given:

$$K = \frac{\Delta R/R}{\Delta l/l}$$

Therefore,

$$\Delta R = K\,R\,\Delta l/l$$

$$\Delta R = 2 \times 130 \times 1 \times 10^{-6} = 260\ \mu\Omega$$

The initial resistance value R of a strain gauge is typically around 120 Ω and the gauge factor may be from (for Nickel) – 12 to + 6. A gauge factor of 2 is reasonable for most strain gauges. Semiconductor gauge have higher sensitivities.

The strain gauge is normally used in a bridge arrangement in which the gauge forms one arm of the bridge. The bridge may be ac or dc actuated. A simple dc arrangement is shown in Fig. 13.5. Only one of the gauges is an active element, producing an output proportional to the strain. The other (dummy) gauge is not strained, but simply balances the bridge (compensation). Since the resistance of the fine wire element is sensitive to temperature as well as stress variation, any change in temperature will cause a change in the bridge balance conditions. This effect can cause error in the strain measurement (thereby affecting the accuracy). Hence, when temperature variations are significant, or when unusual accuracy is required, some compensation must be used. The dummy gauge accomplishes this, because it is placed in the same temperature environment as the active gauges, but not subjected to strain. Consequently, the temperature causes the same change of resistance in the two strain gauges and the bridge balance is not affected by the temperature.

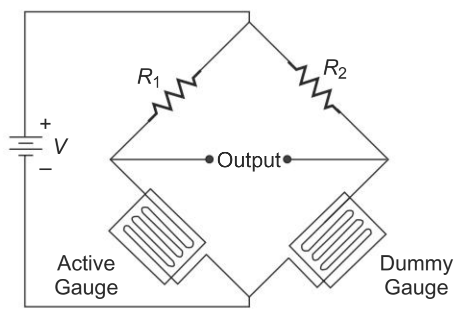


Fig. 13.5 Strain gauge used in bridge arrangement

If the two resistors R_1 and R_2 have negligible temperature coefficients, the bridge retains its balance under conditions of no-strain, at any temperature within its operating range.

(However, one of the two gauges in mounted so that its sensitivity direction is at right angles to the direction of strain.)

The resistance of this dummy gauge is not affected by the deformation of the material and it therefore acts like a passive resistance, with regard to strain measurement.

Since only one gauge responds to the strain, the strain causes bridge unbalance just as in the case of a single gauge.

Advantages of Resistance Thermometers The measurement of temperature by the electrical resistance method has the following advantages and characteristics.

1. The measurement is very accurate.
2. It has a lot of flexibility with regard to choice of measuring equipment.
3. Indicators, recorders or controllers can also be operated.
4. More than one resistance element can be clubbed to the same indicating/recording instrument.
5. The temperature sensitive resistance element can be easily installed and replaced.
6. The accuracy of the measuring circuit can be easily checked by substituting a standard resistor for the resistive element.
7. Resistive elements can be used to measure differential temperature.
8. Resistance thermometers have a wide working range without loss of accuracy, and can be used for temperature ranges (–200°C to + 650°C).
9. They are best suited for remote indication.
10. The resistive element response time is of the order of 2 to 10s
11. The limits of error of a resistive element are ± 0.25% of the scale reading.
12. The size of the resistive element may be about 6 – 12 mm in diameter and 12 – 75 mm in length.
13. Extremely accurate temperature sensing.
14. No necessity of temperature compensation.
15. Stability of performance over long periods of time.

Limitations of Resistance Thermometer

1. High cost
2. Need for bridge circuit and power source
3. Possibility of self-heating
4. Large bulb size, compared to a thermocouple

THERMISTOR 13.8

The electrical resistance of most materials changes with temperature. By selecting materials that are very temperature sensitive, devices that are useful in temperature control circuits and for temperature measurements can be made.

Thermistor (THERMally sensitive resISTOR) are non-metallic resistors (semiconductor material), made by sintering mixtures of metallic oxides such as manganese, nickel, cobalt, copper and uranium.

Thermistors have a Negative Temperature Coefficient (NTC), i.e. resistance decreases as temperature rises. Figure 13.12 shows a graph of resistance vs temperature for a thermistor. The resistance at room temperature (25°C) for typical commercial units ranges from 100 Ω to 10 MΩ. They are suitable for use only up to about 800°C. In some cases, the resistance of thermistors at room temperature may decrease by 5% for each 1°C rise in temperature. This high sensitivity to temperature changes makes the thermistor extremely useful for precision temperature measurements, control and compensation.

The smallest thermistors are made in the form of beads. Some are as small as 0.15 mm (0.006 in.) in diameter. These may come in a glass coating or sealed in the tip of solid glass probes. Glass probes have a diameter of about 2.5 mm and a length which varies from 6 – 50 mm. The probes are used for measuring the temperature of liquids. The resistance ranges from 300 Ω to 100 MΩ.

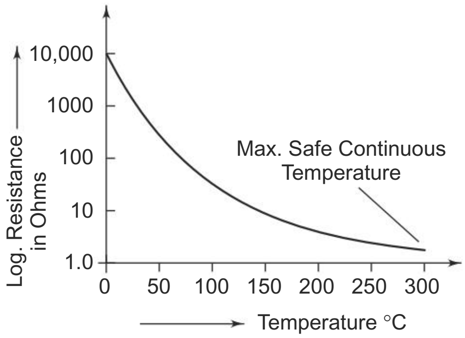


Fig. 13.12 Resistance vs temperature graph of a thermistor

Where greater power dissipations is required, thermistors may be obtained in disc, washer or rod forms.

Disc thermistors about 10 mm in diameter, either self supporting or mounted on a small plate, are mainly used for temperature control. These thermistors are made by pressing themistors material under several tons of pressure in a round die to produce flat pieces 1.25 – 25 mm in diameter and 0.25 – 0.75 mm thick, having resistance values of 1 Ω to 1 MΩ. These are sintered and coated with silver on two flat surfaces.

Washer thermistors are made like disc thermistors, except that a hole is formed in the centre in order to make them suitable for mounting on a bolt. Rod thermistors are extruded through dies to make long cylindrical units of 1.25, 2.75, and 4.25 mm in diameter and 12.5 – 50 mm long. Leads are attached to the end of the rods. Their resistance usually varies from 1 – 50 kΩ.

The advantage of rod thermistors over other configurations is the ability to produce high resistance units with moderately high power handling capability.

Thermistors can be connected in series/parallel combinations for applications requiring increased power handling capability. High resistance units find application in measurements that employ low lead wires or cables.

Thermistors are chemically stable and can be used in nuclear environments. Their wide range of characteristics also permits them to be used in limiting and regulation circuits, as time delays, for integration of power pulses, and as memory units.

Typical thermistor configurations are as shown in Fig. 13.13(a). Figure 13.13(b) shows a bush type thermistor.

A thermistor in one arm of a Wheatstone bridge provides precise temperature information. Accuracy is limited, in most applications, only by the readout devices.

Thermistors are non-linear devices over a temperature range, although now units with better than 0.2% linearity over the 0–100°C temperature range are available. The typical sensitivity of a thermistor is approximately 3 mV/°C at 200°C.

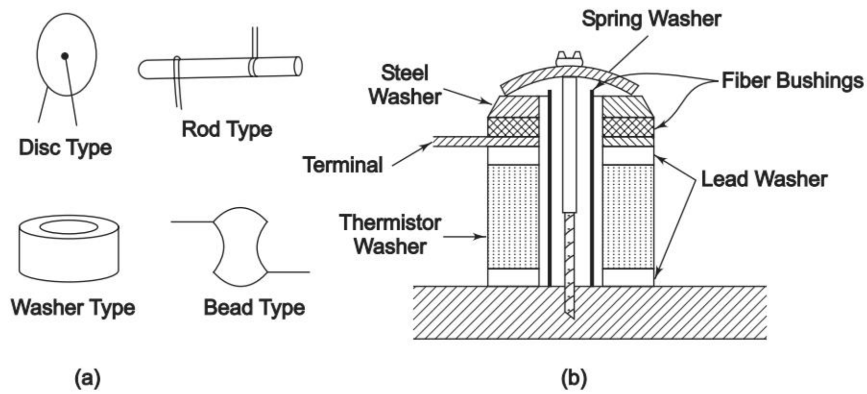


Fig. 13.13 (a) Various configurations of thermistor (b) Bush-type thermistor

Advantages of Thermistor

1. Small size and low cost.
2. Fast response over narrow temperature range.
3. Good sensitivity in the NTC region.
4. Cold junction compensation not required due to dependence of resistance on absolute temperature.
5. Contact and lead resistance problems not encountered due to large R_{th} (resistance).

Limitations of Thermistor

1. Non-linearity in resistance vs temperature characteristics.
2. Unsuitable for wide temperature range.
3. Very low excitation current to avoid self-heating.
4. Need of shielded power lines, filters, etc. due to high resistance.

Example 13.4 *The circuit of Fig. Ex. 13.2 (a) is to be used for temperature measurement. The thermistor is a 4 kΩ type. The meter is a 50 mA meter with a resistance of 3 Ω, R_c is set to 17 Ω, and supply V_t is 15 V. What will be the meter reading at 77°F (25°C) and at 150°F.*

Solution From the graph of temperature versus resistance, the resistance at 25°C is 4 kΩ. Therefore the current at 25°C is

$$I = \frac{V_t}{R_t} = \frac{15}{4000 + 17 + 3} = \frac{15}{4020} = 3.73 \text{ mA.}$$

At 150°F, the graph shows that the thermistor resistance is approximately 950 Ω. The meter reading will then be

$$I = \frac{V_t}{R_t} = \frac{15}{950 + 17 + 3} = \frac{15}{970} = 15.5 \text{ mA.}$$

Whenever the iron bar at point A moves and alters the air gap, the bridge becomes unbalanced by an amount proportional to the change in inductance, which in turn is proportional to the displacement of the moving member.

The increase and decrease of the inductance with varying air gap sizes is non-linear, and so is the output. Also, the flux density within the air gaps is easily affected by external fields.

Example 13.5 *A variable reluctance type inductive transducer has a coil of inductance of 2500 μH When the target made of ferromagnetic material is 1mm away from the core. Calculate the value of inductance when a displacement of 0.04 mm is applied to the target in a direction moving it towards the core .*

Solution Given inductance with gap length of 1 mm is $L = 2500\ \mu\text{H}$

Step 1: Length of air gap when a displacement is applied to the target

$$= 1.00 - 0.04 = 0.96 \text{ mm}$$

Step 2: Now inductance is inversely proportional to the length of air gap

Therefore 'L' with gap length of 0.96 mm

$$= L + \Delta L = 2500\ \mu\text{H} \times \frac{1}{0.96 \text{ mm}} = 2604\ \mu\text{H}$$

Step 3: Therefore, change in inductance

$$\Delta L = 2604\ \mu\text{H} - 2500\ \mu\text{H} = 104\ \mu\text{H}$$

DIFFERENTIAL OUTPUT TRANSDUCERS 13.10

The differential output transducer consists of a coil which is divided into two parts, as shown in Figs. 13.17(a) and (b).

(Inductive transducers using self inductance as a variable use one coil, while those using mutual inductance as a variable use multiple coils.)

Normally the change in self inductance, ΔL, for inductive transducers, (working on the principle of change of self inductance) is not sufficient for detection of subsequent stages of the instrumentation system.

However, if successive stages of the instrument respond to ΔL or ΔM, rather than $L + \Delta L$, or $M + \Delta M$, the sensitivity and accuracy will be much higher.

The transducers can be designed to provide two outputs, one of which represents inductance (self or mutual) and the other the decrease in inductance (self or mutual). The succeeding stages of the instrumentation system measure the difference between these outputs. This is known as differential output.

Advantages of Differential Output

1. Sensitivity and accuracy are increased.
2. Output is less affected by external magnetic fields.
3. Effective variations due to temperature changes are reduced.
4. Effects of change in supply voltages and frequency are reduced.

In response to a physical signal (which is normally displacement), the inductance of one part increases from L to $L + \Delta L$, while that of the other part decreases from L to $L - \Delta L$. The change is measured as the difference of the two, resulting in an output of $2\ \Delta L$ instead of ΔL, when one winding is used. This increases the sensitivity and also eliminates error.

Inductive transducers using the change in the number of turns to cause a change in the self inductance are shown in Fig. 13.17.

Figure 13.17(a) is used for measurement of linear displacement using an air cored coil.

Figure 13.17(b) is used for the measurement of angular displacement using an iron cored coil.

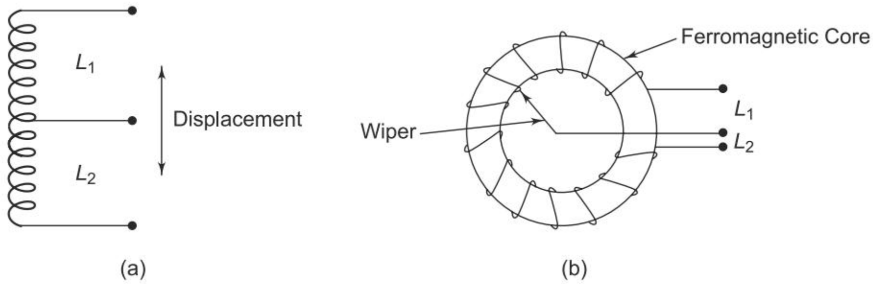


Fig. 13.17 (a) Linear differential output transducer (b) Angular differential output transducer

Figure 13.18 shows an inductive transducer giving a differential output. The output represents a change of self inductance due to change of reluctance. (This inductive transducer also works on the principle of change of self inductance of the two coils with change in reluctance of the path of the magnetic circuit. The target as well as cores on which the coil is wound are made up of iron.)

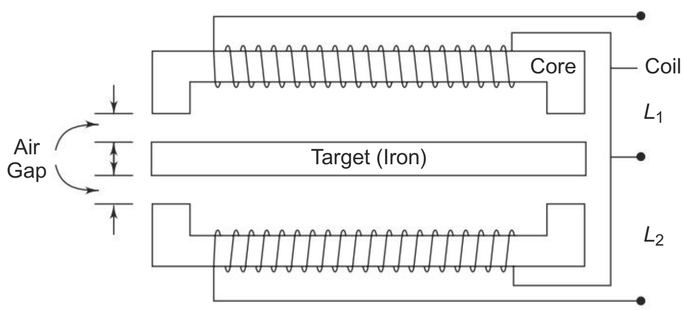


Fig. 13.18 Inductive transducer differential output (Reluctance principle)

LINEAR VARIABLE DIFFERENTIAL TRANSDUCER (LVDT) 13.11

The differential transformer is a passive inductive transformer. It is also known as a Linear Variable Differential Transformer (LVDT). The basic construction is as shown in Fig. 13.19.

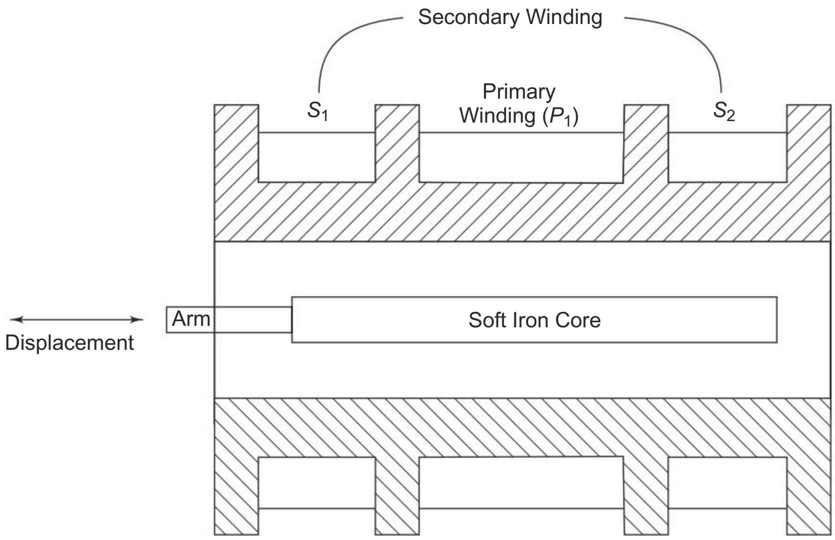


Fig. 13.19 Construction of a linear variable differential transducer (LVDT)

The transformer consists of a single primary winding P_1 and two secondary windings S_1 and S_2 wound on a hollow cylindrical former. The secondary windings have an equal number of turns and are identically placed on either side of the primary windings. The primary winding is connected to an ac source.

An movable soft iron core slides within the hollow former and therefore affects the magnetic coupling between the primary and the two secondaries.

The displacement to be measured is applied to an arm attached to the soft iron core.

(In practice, the core is made up of a nickel-iron alloy which is slotted longitudinally to reduce eddy current losses.)

When the core is in its normal (null) position, equal voltages are induced in the two secondary windings. The frequency of the ac applied to the primary winding ranges from 50 Hz to 20 kHz.

The output voltage of the secondary windings S_1 is E_{S1} and that of secondary winding S_2 is E_{S2}.

In order to convert the output from S_1 to S_2 into a single voltage signal, the two secondaries S_1 and S_2 are connected in series opposition, as shown in Fig. 13.20.

Hence the output voltage of the transducer is the difference of the two voltages. Therefore the differential output voltage $E_o = E_{S1} \sim E_{S2}$.

When the core is at its normal position, the flux linking with both secondary windings is equal, and hence equal emfs are induced in them. Hence, at null position $E_{S1} = E_{S2}$. Since the output voltage of the transducer is the difference of the two voltages, the output voltage E_o is zero at null position.

Now, if the core is moved to the left of the null position, more flux links with winding S_1 and less with winding S_2. Hence, output voltage E_{S1} of the secondary winding S_1 is greater than E_{S2}. The magnitude of the output voltage of the secondary is then $E_{S1} - E_{S2}$, in phase with E_{S1} (the output voltage of secondary winding S_1).

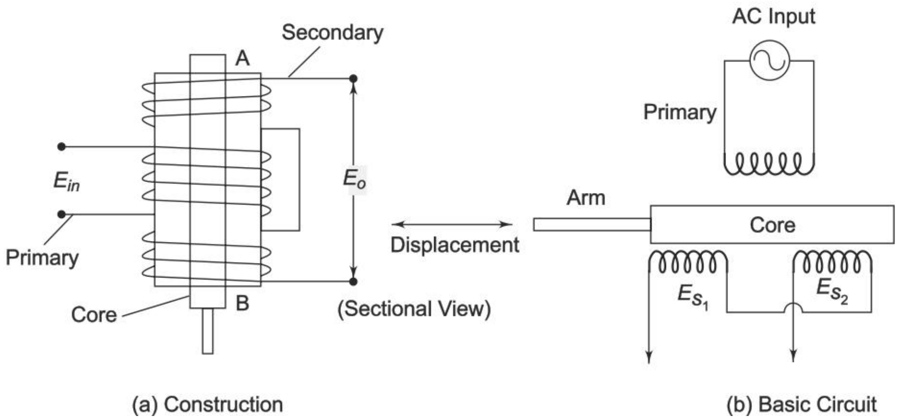


Fig. 13.20 Secondary winding connected for differential output

Similarly, if the core is moved to the right of the null position, the flux linking with winding S_2 becomes greater than that linked with winding S_1. This results in E_{S2} becoming larger than E_{S1}. The output voltage in this case is $E_o = E_{S2} - E_{S1}$ and is in phase with E_{S2}.

The amount of voltage change in either secondary winding is proportional to the amount of movement of the core. Hence, we have an indication of the amount of linear motion. By noting which output is increasing or decreasing, the direction of motion can be determined. The output ac voltage inverts as the core passes the centre position. The farther the core moves from the centre, the greater the difference in value between E_{S1} and E_{S2} and consequently the greater the value of E_o. Hence, the amplitude is function of the distance the core has moved, and the polarity or phase indicates the direction of motion, as shown in Fig. 13.21.

As the core is moved in one direction from the null position, the difference voltage, i.e. the difference of the two secondary voltages increases, while maintaining an in-phase relation with the voltage from the input source. In the other direction from the null position, the difference voltage increases but is 180° out of phase with the voltage from the source.

By comparing the magnitude and phase of the difference output voltage with that of the source, the amount and direction of the movement of the core and hence of the displacement may be determined.

The amount of output voltage may be measured to determine the displacement. The output signal may also be applied to a recorder or to a controller that can restore the moving system to its normal position.

The output voltage of an LVDT is a linear function of the core displacement within a limited range of motion (say 5 mm from the null position).

Figure 13.21(d) shows the variation of the output voltage against displacement for various position of the core. The curve is practically linear for small displacements (up to 5 mm). Beyond this range, the curve starts to deviate.

The diagram in Figs 13.21(a), (b) and (c) shows the core of an LVDT at three different positions.

In Fig. 13.21(b), the core is at O, which is the central zero or null position. Therefore, $E_{S1} = E_{S2}$ and $E_o = 0$.

When the core is moved to the left, as in Fig. 13.21(a) and is at A, E_{S1} is more than E_{S2} and E_o is positive. This movement represents a positive value and therefore the phase angle, is $\phi = 0°$.

When the core is moved to the right towards B, E_{S2} is greater than E_{S1} and hence E_o is negative. Therefore, S_2 the output voltage is 180° out of phase with the voltage which is obtained when the core is moved to the left. The characteristics are linear from $O - A$ and $O - B$, but after that they become non-linear.

One advantage of an LVDT over the inductive bridge type is that it produces higher output voltage for small changes in core position. Several commercial models that produce 50 mV/mm to 300 mV/mm are available. 300 mV/mm implies that a 1 mm displacement of the core produces a voltage output of 300 mV.

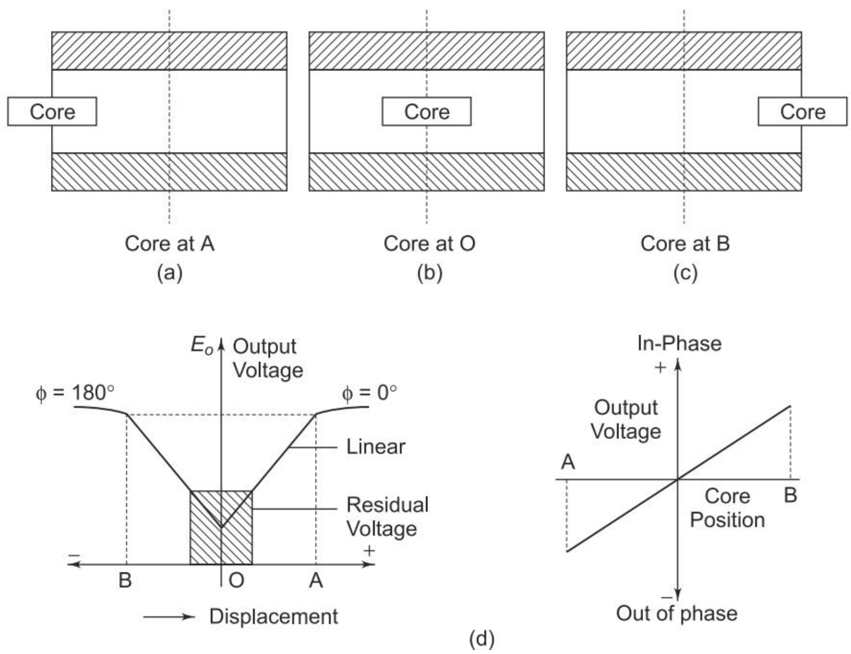


Fig. 13.21 (a), (b), (c) Various core position of LVDT
(d) Variation of output voltage vs displacement

LVDTs are available with ranges as low as ± 0.05 in. to as high as ± 25 in. and are sensitive enough to be used to measure displacements of well below 0.001

in. They can be obtained for operation at temperatures as low as – 265°C and as high as + 600°C and are also available in radiation resistance designs for nuclear operations.

Advantages of LVDT

1. ***Linearity*** The output voltage of this transducer is practically linear for displacements upto 5 mm (a linearity of 0.05% is available in commercial LVDTs).
2. ***Infinite resolution*** The change in output voltage is stepless. The effective resolution depends more on the test equipment than on the transducer.
3. ***High output*** It gives a high output (therefore there is frequently no need for intermediate amplification devices).
4. ***High sensitivity*** The transducer possesses a sensitivity as high as 40 V/mm.
5. ***Ruggedness*** These transducers can usually tolerate a high degree of vibration and shock.
6. ***Less friction*** There are no sliding contacts.
7. ***Low hysteresis*** This transducer has a low hysteresis, hence repeatability is excellent under all conditions.
8. ***Low power consumption*** Most LVDTs consume less than 1 W of power.

Disadvantages

1. Large displacements are required for appreciable differential output.
2. They are sensitive to stray magnetic fields (but shielding is possible).
3. The receiving instrument must be selected to operate on ac signals, or a demodulator network must be used if a dc output is required.
4. The dynamic response is limited mechanically by the mass of the core and electrically by the applied voltage.
5. Temperature also affects the transducer.

Example 13.6 *An ac LVDT has the following data.*

Input = 6.3 V, Output = 5.2 V, range ± 0.5 in. Determine

(i) Calculate the output voltage vs core position for a core movement going from + 0.45 in. to – 0.30 in.

(ii) The output voltage when the core is – 0.25 in. from the centre.

Solution

(i) 0.5 in. core displacement produces 5.2 V, therefore a 0.45 in. core movement produces (0.45 × 5.2)/0.5 = 4.68 V.
Similarly a – 0.30 in. core movement produces

$$(-0.30 \times -5.2)/(-0.5) = -3.12 \text{ V}$$

(ii) – 0.25 in. core movement produces

$$(-0.25 \times -5.2)/(-0.5) = -2.6 \text{ V}$$

13. Extremely accurate temperature sensing.
14. Performance stability over longer periods of time

Limitations of Resistance Thermometer

1. High cost
2. Need for bridge and power source
3. Possibility of self heating.

13.20.5 Thermistors

We have already discussed thermistors in detail in Sec. 13.8.

13.20.6 Thermocouple

One of the most commonly used methods of measurement of moderately high temperature is the thermocouple effect. When a pair of wires made up of different metals is joined together at one end, a temperature difference between the two ends of the wire produces a voltage between the two wires as illustrated in Fig. 13.42

Temperature measurement with Thermocouple is based on the Seebeck effect. A current will circulate around a loop made up of two dissimilar metal when the two junctions are at different temperatures as shown in Fig. 13.43.

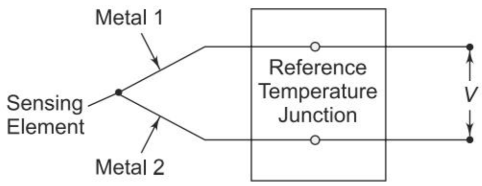


Fig. 13.42 Basic Thermocouple Connection

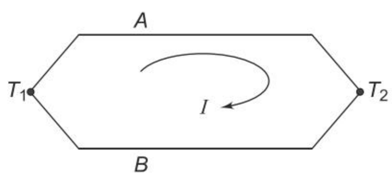


Fig. 13.43 Current through two dissimilar Metals

When this circuit is opened, a voltage appears that is proportional to the observed seebeck current.

There are four voltage sources, their sum is the observed seebeck voltage. Each junction is a voltage source, known as *Peltier emf*. Furthermore, each homogenous conductor has a self induced voltage or Thomson emf.

The Thomson and Peltier emfs originate from the fact that, within conductors, the density of free charge carriers (electrons and holes) increases with temperature.

(If the temperature of one end of a conductor is raised above that of the other end, excess electrons from the hot end will diffuse to the cold end. This results in an induced voltage, the *Thomson effect*, that makes the hot end positive with respect to the cold end.

Conductors made up of different materials have different free-carriers densities even when at the same temperature. When two dissimilar conductors are joined, electrons will diffuse across the junction from the conductor with higher electron density. When this happens the conductor losing electrons acquire a positive voltage with respect to the other conductor. This voltage is called the *Peltier emf*.)

When the junction is heated a voltage is generated, this is known as seebeck effect. The seebeck voltage is linearly proportional for small changes in temperature. Various combinations of metals are used in Thermocouple's.

The magnitude of this voltage depends on the material used for the wires and the amount of temperature difference between the joined ends and the other ends. The junction of the wires of the thermocouple is called the *sensing junction*, and this junction is normally placed in or on the unit under test.

Since it is the temperature difference between the sensing junction and the other ends that is the critical factor, the other ends are either kept at a constant reference temperature, or in the case of very low cost equipment at room temperature. In the latter case, the room temperature is monitored and thermocouple output voltage readings are corrected for any changes in it.

Because the temperature at this end of the thermocouple wire is a reference temperature, this function is known as the reference, also called as the *cold junction*.

A thermocouple, therefore consists of a pair of dissimilar metal wires joined together at one end (sensing or hot junction) and terminated at the other end (reference or cold junction), which is maintained at a known constant temperature (reference temperature). When a temperature difference exists between the sensing junction and the reference junction, an emf is produced, which causes current in the circuit.

When the reference end is terminated by a meter or a recording device, the meter indication will be proportional to the temperature difference between the hot junction and the reference junction.

The magnitude of the thermal emf depends on the wire materials used and in the temperature difference between the junctions.

Figure 13.44 shows the thermal emfs for some common thermocouple materials. The values shown are based on a reference temperature of 32°F.

The thermpcouple (TC) is a temperature transducer that develops an emf that is a function of the temperature difference between its hot and cold junctions.

A thermocouple may be regarded as a thermometer based on thermo-emf and works on the principle that the potential between two dissimilar metals or metal alloys is a function of temperature.

Type 'E' Thermocouple units use Chromel alloy as the positive electrode and constantan alloy as the negative electrode.

Type 'S' Thermocouple produces the least output voltage but can be used over greatest temperature range.

Type 'T' shown in Fig. 13.45, uses copper and constantan.

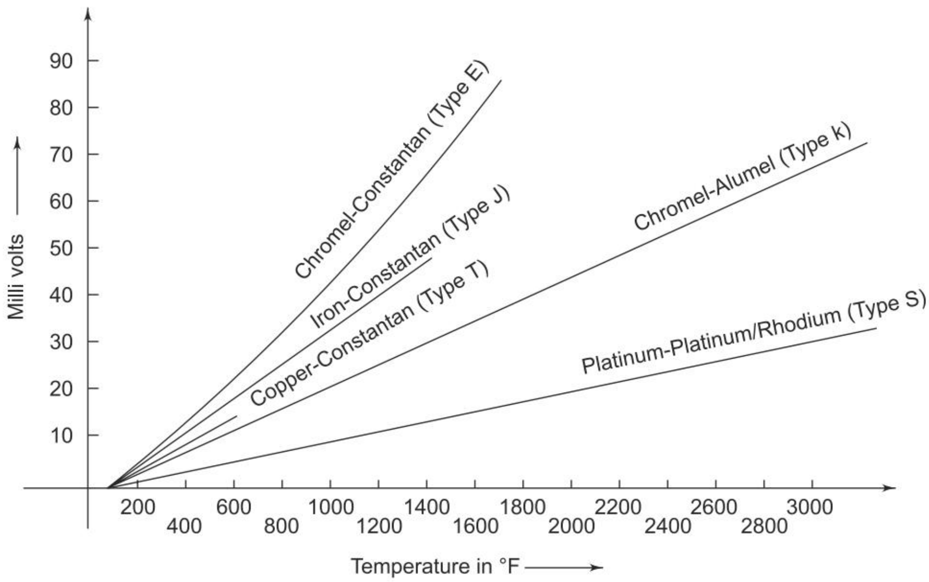


Fig. 13.44 Thermocouple output voltage as a function of temperature for various thermocouple materials

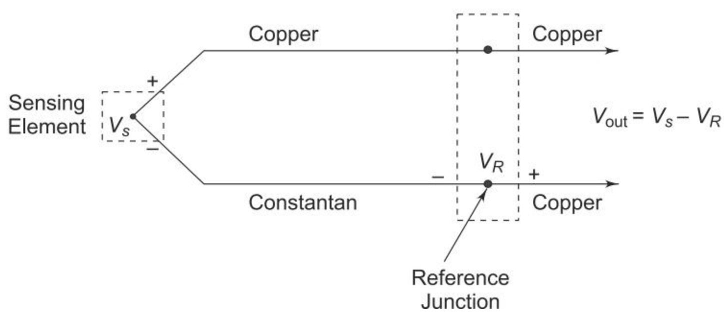


Fig. 13.45 A type t thermocouple with reference junction

Copper used, is an element and constantan used is an alloy of nickel and copper. The copper side is positive and constantan side is negative. Assuming copper wires used to connect the thermocouple to the next stage (circuit), a second Copper-Constantan junction is (formed) produced. This junction is called as the reference junction. It generates a Seebeck voltage that opposes the voltage generated by the sensing junction. If both junctions are at the same temperature, the output voltage V_{out} will be zero. If the sensing junction is at a higher temperature, V_{out} will be proportional to the difference between the two junction temperature. The temperature cannot be derived directly from the output voltage alone. It is subjected to an error caused by the voltage produced by the reference junction. This can be overcome by placing the reference junction in an ice bath to keep it at a known temperature. This process is called as *cold junction* *compensation* as shown in Fig.13.46(a). The reference voltage is maintained at 0°C. The reference voltage is now predictable from the calibration curve of the type 'T' thermocouple.

When copper is not one of thermocouple metal then four junction circuit is formed. The type 'J' thermocouple uses iron and constantan as the two elements shown in Fig.13.46(b). When it is connected to copper wires, two iron copper junctions result. These junctions present no additional difficulties because of the *isothermal block* used. This block is made of material that is a poor conductor of electricity but a good conductor of heat. Both Iron–Copper junctions will be at the same temperature and generate the same Seeback voltage and hence these two voltages will cancel. Cold junction compensation is also used as the Reference junction in this case.

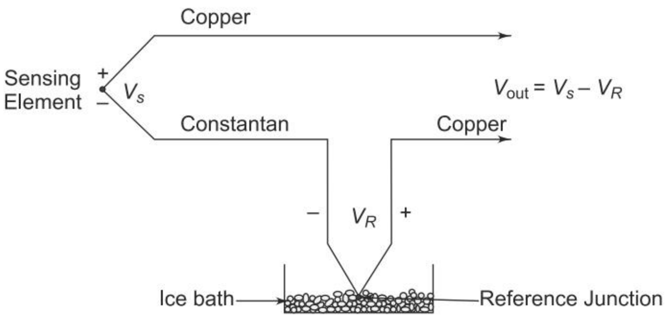


Fig. 13.46 (a) Cold junction compensation

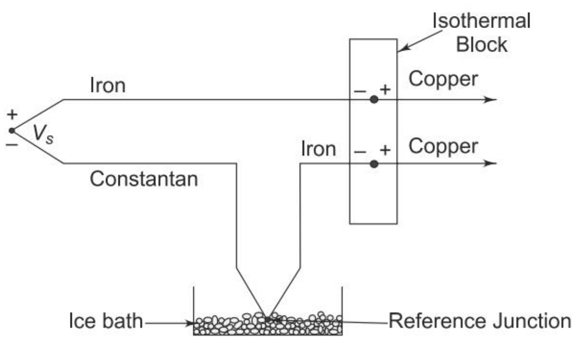


Fig. 13.46 (b) Type J thermocouple using isothermal block

The ice-baths method is not the most convenient method, to compensate the reference junction. This technique is often used in the calibration laboratory. Industry uses a different method of reference junction compensation as shown in Fig.13.47.

The isothermal block contains two reference junctions and a thermistor. The resistance of the thermistor is a function of temperature. A circuit is used to sense this resistance and to compensate for the voltage introduced by the two reference junctions. This arrangement is sometimes called as *Electronic ice point reference*.

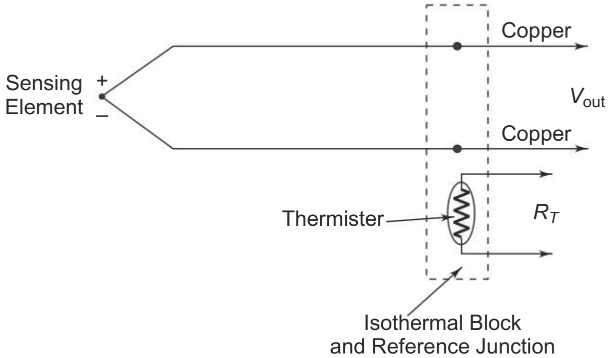


Fig. 13.47 Reference junction compensation used in industry

If the sensor is interfaced to a computer, the reference temperature will be converted to a reference voltage and then subtracted from the output voltage V_{out}. This process is known as *Software Compensation*.

An isothermal block with one temperature sensor can provide compensation for several units.

Table 13.3 gives the construction and thermoelectric properties of various thermocouples.

Table 13.3 Different Types of Thermocouples

Thermocouple type	*Materials used*	*Temperature range/ °C*	*Sensitivity µV/ °C*
Type T	Copper/Constantan	–200–400	15–60
E	Chromel/Constantan	0–850	40–55
J	Iron / Constantan	–200–900	45–57
K	Chromel/Alumel	–200–1250	40–55
R	Platinum/Platinum 13% Rhodium	0–1600	5–12
S	Platinum/Platinum 10% Rhodium	0–1500	5–12
B	Platinum 6% Rhodium/ Platinum 30% Rhodium	30–1800	0.3–0.8
G	Tungsten/Tungsten 26% Rhenium	15–2800	3–20
C	Tungsten 5% Rhenium/ Tungsten 25% Rhenium	0–2750	10–20

For accurate measurement of hot junction temperature, the cold junction or the reference junction should be kept at 0 °C. If the reference junction is kept at the ambient temperature, then a voltage corresponding to this temperature must be added to the measurement to obtain accurate reading.

Most modern thermocouple measurement systems employ electrical cold junction (an electronic circuit which simulates the voltage that the reference junction would generate at ambient temperature) compensation. A popular technique used for reference junction compensation used in data loggers and data acquisition systems is shown in Fig. 13.48.

The measuring junction's terminals are screwed on an isothermal block (the temperature of which remains uniform within ± 0.05 °C). The temperature of the isothermal block is measured independently and compensating voltage is generated using electronic circuitry. This compensation voltage is combined with the emf from measuring junction to obtain the true temperature

Thermocouples are sometimes connected in series or parallel to provide increased voltage or current output.

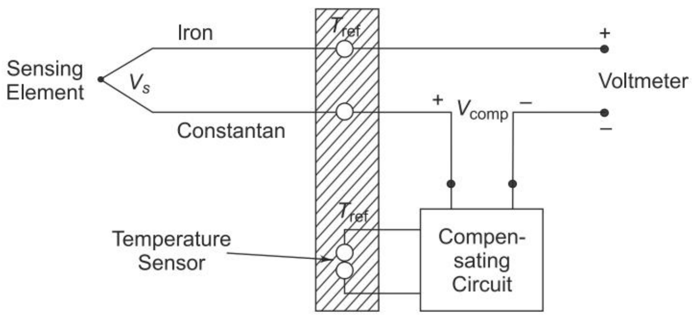


Fig. 13.48 Practical isothermal block reference junction for data loggers, etc.

In Fig.13.49(a), four thermocouples are connected in series, with wire *A* being positive and *B* being negative in each thermocouple.

The total emf between points 1 to 5 is the sum of individual thermocouple emf. An arrangement of this type is called a *Thermopile* and is used to obtain increased sensitivity and greater absolute emf from a thermocouple installation.

Figure 13.49(b) shows four thermocouples in parallel. This arrangement provides a large current but emf is same as that of any one thermocouple.

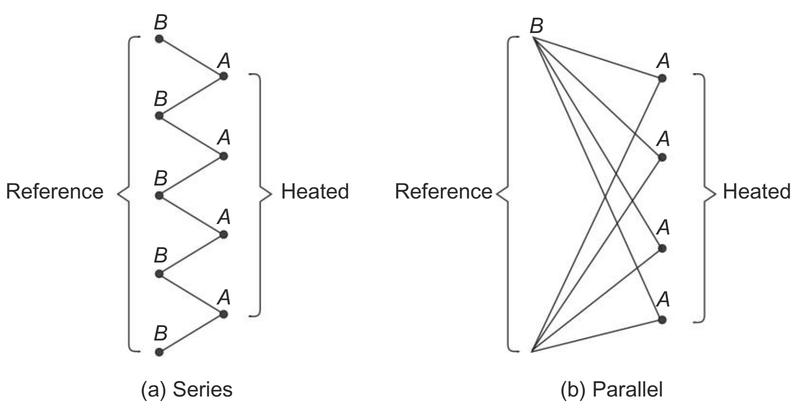


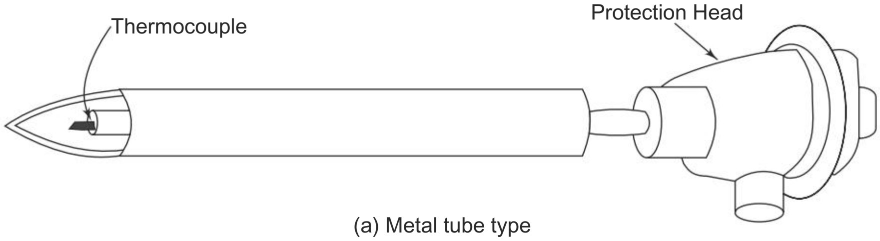
Fig. 13.49 Thermocouples in series and parallel (Thermopile)

Thermocouples must be protected from mechanical damage and isolated from corrosive or contaminating effect that most gases and liquids have at high temperature. The device used for this purpose are called *wells* or *tubes* depending upon their physical construction or *thermowells*.

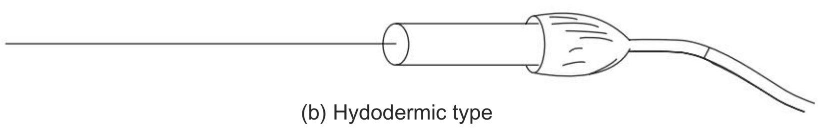
Thermocouples are made from a number of different metal alloys, covering a wide range of temperature from as low as –270 °C (–418 °F) to as high as 2700 °C (about 5000 °F). They may be obtained in a simple uninsulated wire form, in insulated form or inside protective sheaths or probes (sheath diameter as small as 0.25 mm).

The thermo-junction is protected from contamination from the process materials by enclosing it in a protective sheath. For example, a cupro-nickel sheath for copper/chromel thermocouple and mild sheath for iron/chromel thermocouples.

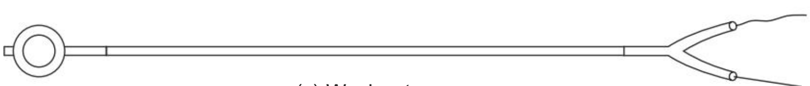
The temperature ranges covered by thermocouples make them appropriate for use in industrial furnaces as well as for measurement in the cryogenic range. Different types of thermocouples are as shown in Fig. 13.50.



(a) Metal tube type



(b) Hydodermic type



(c) Washer type

Fig. 13.50 Different type of thermocouples

Advantages of Thermocouple

1. It has rugged construction.
2. It has a temperature range from –270 °C–2700 °C.
3. Using extension leads and compensating cables, long distances transmission for temperature measurement is possible.
4. Bridge circuits are not required for temperature measurement.
5. Comparatively cheaper in cost.
6. Calibration checks can be easily performed.
7. Thermocouples offer good reproducibility.
8. Speed of response is high compared to the filled system thermometer.

9. Measurement accuracy is quite good.

Disadvantages of Thermocouple

1. Cold junction and other compensation is essential for accurate measurements.
2. They exhibit non-linearity in the emf versus temperature characteristics.
3. To avoid stray electrical signal pickup, proper separation of extension leads from thermocouple wire is essential.
4. Stray voltage pick-up are possible.
5. In many applications, the signals need to be amplified.

13.20.7 Semiconductor Diode Temperature Sensor

Semiconductor diode is a versatile device and finds use in many applications. Two of its parameter, that is forward voltage drop (V_f) and reverse saturation current (I_s) are temperature sensitive. The sensitivity of I_s with temperature is non-linear, but V_f has a linear temperature coefficient over a wide temperature range. Hence, V_f can serve as the basis for electronic thermometers

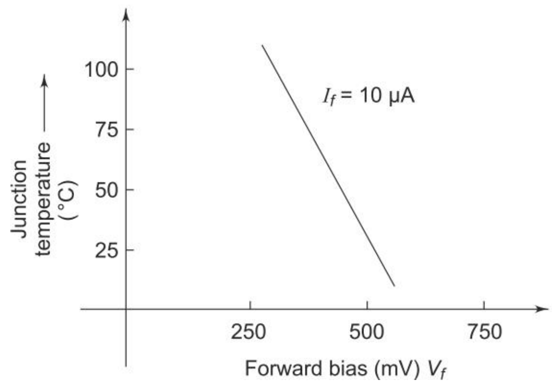


Fig.13.51 Characteristics of forward bias (V_f) versus temperature

Figure 13.51 shows the characteristics of V_f versus temperature for a typical silicon pn junction diode. The linearity of this characteristics at high values of temperature is affected by the following factors.

1. Dependence of V_f on I_s which is also temperature sensitive.
2. Presence of finite surface leakage component across the pn junction.
3. Finite resistance of the bulk semiconductor used for the diode structure.

The limitations introduced by point 1 can be overcomed by using a pair of well-matched junction transistors in a differential configuration to serve as the temperature sensors.

If the two transistors are operated at widely different emitter current values, the resulting V_{BE}, Base emitter differential voltage can serve as an excellent index of temperature.