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S K SINGH

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Part I
Measurement Concepts

1

Basic Concepts and Qualities of Measurement

1.1 INTRODUCTION

The basic purpose of instrumentation in a process is to obtain the requisite information pertaining to the successful completion of the process. A broad definition of instrumentation may be given as follows:

Instrumentation is the philosophy based on:

(i) the preposition that the condition of human society and of industrial processes and operations, i.e. the force of nature, should be controlled,

(ii) the principle that, before a condition can be controlled, it must be measured,

(iii) the dictum that, in order to measure a condition or property, it must be segregated, and

(iv) the logic "If you control it manually you should control it automatically."

The progress of instrumentation in industry, as it is known today, took place largely in the 1930s, but began with the introduction of a reliable instrument for recording temperature. With the growth of continuous manufacturing, the need for continuous measurement of pressure, temperature, level, flow, etc. became urgent. There are continuous demands for improvements in the quality of measurement and for development of new methods based on newly found physical and chemical laws and effects.

1.2 MEASUREMENT AND ITS AIM

Measuring is as old as civilization. It is an essential part of the interaction between humanity and the physical world. It gives us a repeatable and dependable way of quantifying the world in which we live. The process of measuring is essentially that of comparing some unknown value with a value which is assumed to be known. The latter is called a *standard*. A measurement system (perhaps called an *instrument* or *scale* or *meter* or *analyzer*) is a device designed to facilitate this comparison.

Therefore, measurement is a comparison of a given unknown quantity with one of its predetermined standard values adopted as a unit. The result of any measurement is a concrete number consisting of a unit of measurement having its particular name and the number which shows how many times this particular unit is contained in the quantity being measured.

The primary purpose of measurement in process industries and industrial manufacturing is to aid in the economics of industrial operations by improving the quality of the product and efficiency of production. For this purpose and for the maintenance of proper operation, measurement is very important.

1.3 THE FUNCTIONAL ELEMENTS OF AN INSTRUMENT

All instruments contain various parts that perform prescribed functions in converting a variable quantity or condition into a corresponding indication. Thus, the operation of an instrument can be described in terms of the functional elements (various parts) of instrument systems. The functional elements of an instrument are indicated by various blocks in Fig. 1.1.

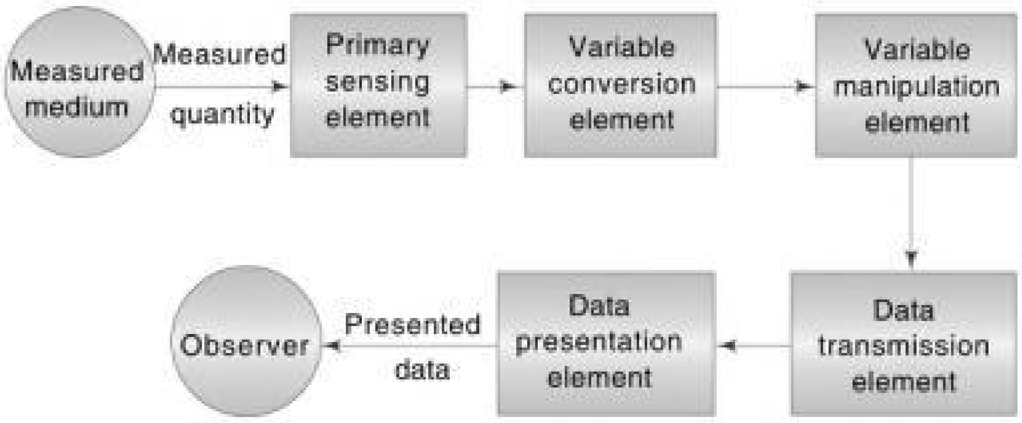


Fig. 1.1 *Functional Elements of an Instrument System*

The primary sensing element of an instrument (Fig. 1.1) is that which first receives energy from the measured medium and produces an output depending in some way on the value of the measured quantity.

A variable-conversion element merely converts the output signal of the primary sensing element (which is some physical variable such as a voltage or a displacement) into a more suitable variable or condition useful to the function of the instrument. It should be noted that every instrument need not include a variable-conversion element, while some require several.

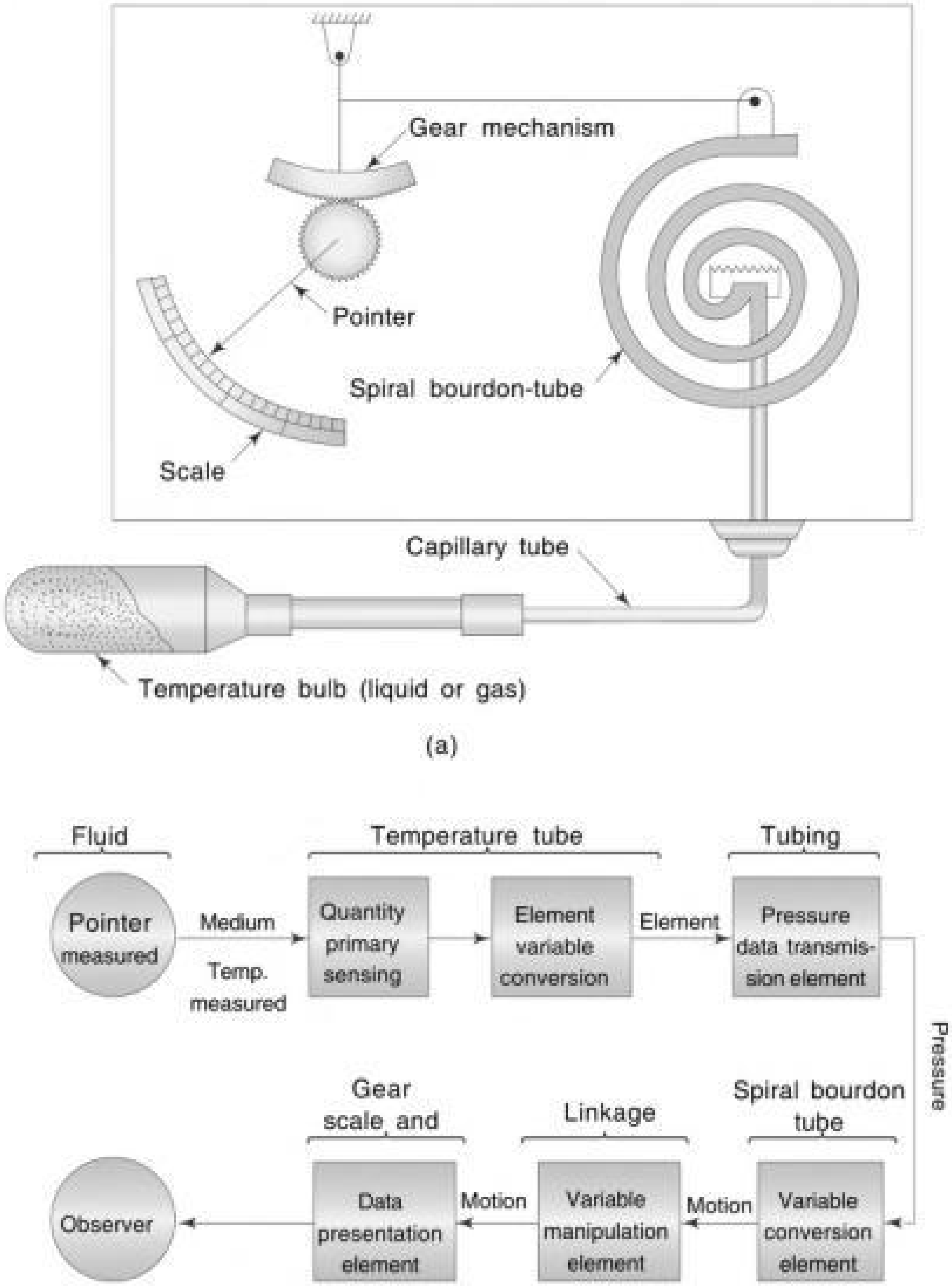
A variable-manipulation element manipulates the signal represented by some physical variable, to perform the intended task of an instrument. In the manipulation process, the physical nature of the variable is preserved. A variable-manipulation element does not necessarily follow a variable-conversion element; it may precede it, appear elsewhere in the chain, or not appear at all.

A data-transmission element transmits the data from one element to the other. It may be as simple as a shaft-and-bearing assembly or as complicated as a telementry system for transmitting signals from one place to another.

A data-presentation element performs the translation function, such as the simple indication of a pointer moving over a scale or the recording of a pen moving over a chart.

The elements of the instrument of Fig. 1.1 do not necessarily appear in all instruments. Figure 1.1 is intended as a vehicle for presenting the concept of functional elements and not as a physical schematic of a generalized instrument. A given instrument may involve the basic functions in any number and combination—they need not appear in the order given in Fig. 1.1.

Figure 1.2 shows a filled thermal system with the various functional elements for process temperature measurement. The liquid- or gas-filled temperature bulb



(a)

(b)

Fig. 1.2 *Filled-system Thermometer* acts as a primary sensing element and variable-conversion element, since a temperature change results in a pressure build-up within the bulb because of the constrained thermal expansion of the filling liquid. This pressure is transmitted through the capillary tube (a data-transmission element) to a spiral, Bourdon-type pressure gauge (a variable-conversion element) which converts the pressure into displacement. The displacement is manipulated by the linkage and gearing (a variable-manipulation element) to give a larger pointer motion. The pointer and scale indicate the temperature, thus serving as data-presentation elements.

1.4 PERFORMANCE CHARACTERISTICS

The performance characteristics of an instrument are very necessary for choosing the most suitable instrument for specific measuring tasks. It can generally be broken down into two sub-areas:

(i) Static characteristics
(ii) Dynamic characteristics

1.4.1 Static Characteristics

The static characteristics of an instrument are, in general, considered for instruments 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 such as accuracy, repeatability, precision, sensitivity, etc. which are also described below.

Calibration Calibration may be defined, in general, as the process for determination, by measurement or comparison with a standard, of the correct value of each scale reading on a meter or other measuring instrument; or determination of the settings of a control device that correspond to particular values of voltage, current, frequency, pressure, flow or some other output.

In performing a calibration of an instrument, the following steps are necessary:

(i) Examine the construction of the instrument and identify and list all the possible inputs.
(ii) Decide, as best as one can, which of the inputs will be significant in the application for which the instrument is to be calibrated.
(iii) Procure apparatus that will allow all significant inputs to vary over the ranges considered necessary.
(iv) By holding some inputs constant, varying others, and recording the output, develop the desired static input-output relations.

Accuracy Accuracy may be defined as the ability of a device or a system to respond to a true value of a measured variable under reference conditions. In actual practice, accuracy is generally and necessarily expressed as the *limit of error* of a measuring device or system under certain operating conditions that may or may not be specified.

Precision Precision is the degree of exactness for which an instrument is designed or intended to perform. It is composed of two characteristics, *conformity* and the number of *significant figures* to which a measurement may be made. Significant figures convey actual information regarding the magnitude and the measurement precision of a quantity. The more significant the figures, the greater the precision of measurement. Now consider, for example, a resistor, whose value of true resistance is 1,592, 154 Ω, measured by a multimeter which consistently and repeatedly indicates 1.5 M Ω. The observer cannot read the true value from the scale. His estimates from the scale reading consistently yield a value of 1.5 M Ω which is as close to the true scale as he can read the scale by estimation. Although there are no deviations from the observed value, the error created by the limitation of the scale reading is a precision error. This example illustrates that conformity is a necessary, but not sufficient condition for precision because of the lack of significant figures obtained.

Repeatability The repeatability of a measuring device may be defined as the closeness of agreement among a number of consecutive measurements of the output for the same value of the input, under the same operating conditions, approaching the measurement from the same direction, and for full-range traverses.

Reproducibility The reproducibility of an instrument is the closeness of agreement among repeated measurements of the output for the same value of input, made under the same operating conditions over a period of time, approaching from both directions. Perfect reproducibility means that the instrument has no drift, i.e. the instrument calibration does not gradually shift over a long period of time such as a week, a month, or even a year.

Drift Drift is an undesired change or a gradual variation in output over a period of time that is unrelated to changes in output, operating conditions, or load. This term most often applies to changes that occur after a specified warm-up period. A long-term calibration drift usually occurs because of the ageing of component parts.

Under laboratory conditions, drift of an element is usually determined in one of the following two ways:

(i) By maintaining exact operating and load conditions and monitoring output variations for a fixed input signal, as a function of time. This is called *point drift*.

(ii) By maintaining input signal, operating conditions, a load approximately constant, and by comparing calibration curves at the beginning and at specified intervals of time. This is called *calibration drift*.

Drift for a measuring device can either be systematic (i.e. approximately predictable in direction and magnitude as a function of time), random (non predictable), or some combination of the two. For most devices, drift is measured and specified as a percentage of output span.

Sensitivity Sensitivity can be defined as the ratio of a change in output to the change in input which causes it, at steady-state conditions. The ratio must be expressed in the units of measurement of output and input.

Usage of this term is generally limited to linear devices where the plot of output to input magnitude is a straight line over the operating range of the device.

The term *sensitivity* is sometimes used to describe the maximum change in an input signal that will not initiate a response on the output.

Resolution Resolution is the least incremental value of input or output that can be detected, caused, or otherwise discriminated by the measuring device. It is often used as an expression of observer error in reading. That is, the resolution of a scale or chart is the minimum error that must be assumed to exist, that can be attributed exclusively to the observation. This is generally considered to be about one-fifth of the smallest scale division. If these least incremental values are considered small, this would be termed *fine resolution*; if they are considered large, this would be termed *coarse resolution*.

Dead Zone Dead zone is the largest range of values of a measured variable to which the instrument does not respond. This is sometimes called *dead spot* and *hysteresis*. Dead zone usually occurs with friction in an indicating or recording instrument, more often in the latter.

Backlash Backlash or mechanical hystersis is defined as that lost motion or free play which is inherent in mechanical elements, such as gears, linkages, or other mechanical-transmission devices that are not rigidly connected.

True Value True value is the error-free value of the measured variable. It is given as

True value = Instrument reading – Static error.

1.4.2 Static Errors

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. Repeated measurement of the same quantity gives different indications.

Mistakes These are errors due to human mistakes, such as careless reading, mistakes in recording observations, incorrect application of a correction, improper application of instruments and computational errors. These errors cannot be treated mathematically. They can be avoided only by taking care in reading and recording the measurement data. One should not be completely dependent on one reading. At least three separate readings should be taken, preferably under conditions in which instruments are switched off and on.

Systematic Errors These types of errors, sometimes referred to as *bias*, influence all measurements of a quantity alike. A constant uniform deviation of the operating point of an instrument is known as a systematic error. There are two types of systematic errors:

(*i*) ***Instrumental errors*** Instrumental errors are the errors inherent in measuring instruments because of their mechanical structure, such as friction in bearings of various moving components, irregular spring tension, stretching of a springs, or reduction in tension due to improper handling or overloading of the instrument. It may be avoided by:

(a) selecting a suitable instrument for the particular measurement application

(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 magnetic or electrostatic fields. It may be avoided by,

(a) providing air conditioning

(b) hermetically sealing certain components in the instrument

(c) use of magnetic shields

Random Errors The cause of such errors is unknown or not determinable in the ordinary process of making measurements. Such errors are normally small and follow the laws of chance. Ramdom errors thus may be treated mathematically according to the laws of probability.

Sources of Errors In the epigraph, Lord Kelvin observes that "*when you can measure what you are speaking about, and express it in numbers, you know something about it*". But that knowledge is never perfect. The measurer must understand the sources of error in the measurement process and must ensure the level of accuracy required for the particular application in question.

The sources of error, other than the inability of a piece of hardware to provide a true measurement, are listed below.

(i) insufficient knowledge of process parameters and design conditions

(ii) poor design

(iii) change in process parameters, irregularities, upsets, etc.

(iv) poor maintenance

(v) errors caused by people who operate instrument equipment

(vi) certain design limitations

1.4.3 Dynamic Characteristics

Instruments rarely respond instantaneously to changes in the measured variable. Instead, they exhibit a characteristic of 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 reactions to take place. Such industrial instruments are nearly always used for measuring quantities that fluctuate with time. Therefore, the dynamic and transient behavior of the instrument is as important as, and often more important than, static behaviour.

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

(i) step change, in which the primary element is subjected to an instantaneous and finite change in measured variable

(ii) linear change, in which the primary element is following a measured variable, changing linearly with time

(iii) 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 speed of response, fidelity, lag, dynamic error, etc.

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

Fidelity It is the degree to which an instrument indicates the changes in measured variable without dynamic error.

Lag It is a retardation or delay in the response of an instrument to changes in the measured quantity.

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.

1.4.4 Dynamic Response

Dynamic Response of Zero-order System The relation between any input and the output can, by application of suitable simplifying assumptions, be written as:

$$a_n \frac{d^n x_0}{dt^n} + a_{n-1} \frac{d^{n-1} x_0}{dt^{n-1}} \ldots + a_1 \frac{dx_0}{dt} + a_0 x_0 = b_m \frac{d^m x_i}{dt^m} + b_{m-1} \frac{d^{m-1} x_i}{dt^{m-1}} + \ldots + b_1 \frac{dx_i}{dt} + b_0 x_i \tag{1.1}$$

where, x_0 = output quantity
x_1 = input quantity
t = time
$a's$, $b's$ = combinations of system physical parameters, assumed constant.

When all the a's and b's other than a_0 and b_0 of the above Eq. (1.1) are assumed to be zero, the differential equation then degenerates into the simple algebraic equation, given as

$$a_0\, x_0 = b_0\, x_i \tag{1.2}$$

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:

$$x_0 = \frac{b_0}{a_0} x_i = K x_i \tag{1.3}$$

where, $$K = \frac{b_0}{a_0} = \text{static sensitivity} \tag{1.4}$$

Since the equation $x_0 = Kx_i$ 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.

Dynamic Response of First-order System If, in Eq. (1.1), all a's and b's other than a_1, a_0 and b_0 are taken as zero, we get:

$$a_1 \frac{dx_0}{dt} + a_0 x_0 = b_0 x_i \tag{1.5}$$

Any instrument that follows the above Eq. (1.5) is defined as a first-order instrument.

By dividing Eq. (1.5) by a_0, the equation can be written as:

$$\frac{a_1}{a_0} \cdot \frac{dx_0}{\mathrm{d}t} + x_0 = \frac{b_0}{a_0} x_i \tag{1.6}$$

or

$$(\tau D + 1)\, x_0 = Kx_i \tag{1.7}$$

where,

$$\tau = \frac{a_1}{a_0} = \text{time constant} \tag{1.8}$$

$$K = \frac{b_0}{a_0} = \text{static sensitivity}$$

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

$$\frac{x_0}{x_i}(D) = \frac{K}{D+1} \tag{1.9}$$

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

Dynamic Response of Second-order System A second-order instrument is defined as one that follows the equation

$$a_2 \frac{d^2 x_0}{dt^2} + a_1 \frac{dx_0}{dt} + a_0 x_0 = b_0 x_i \tag{1.10}$$

The above equation can be reduced as

$$\left(\frac{D^2}{(\omega_n)^2} + \frac{2\xi D}{\omega_n} + 1 \right) x_0 = Kx_i \tag{1.11}$$

where

$$\omega_n = \frac{a_0}{a_2} = \text{undamped natural frequency, in rad/time} \tag{1.12}$$

$$\xi = \frac{a_1}{\sqrt{a_0 a_2}} = \text{damping ratio, dimensionless} \tag{1.13}$$

$$K = \frac{b_0}{a_0} = \text{static sensitivity}$$

The operational transfer function of any second-order instrument is,

$$\frac{x_0}{x_i}(D) = \frac{K}{(D^2/\omega n^2 + 2\xi D/\omega_n + 1)} \tag{1.14}$$

A good example of a second-order instrument is the spring balance.

1.5 STATISTICAL ANALYSIS

The statistical analysis of measurement data is important because it allows an analytical determination of the uncertainty of the final test result. To make statistical analysis meaningful, a large number of measurements is usually required. The systematic errors should also be small as compared to random errors, because statistical analysis of data cannot remove a fixed bias contained in all the measurements.

1.5.1 Arithmetic Mean

The most probable value of a measured variable is the arithmetic mean of the number of readings taken. The best approximation will be made when the number of readings of the same quantity is very large. The arithmetic mean of n measurements at specific count of the variable x is given by the expression,

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n} = \frac{\Sigma x}{n} \tag{1.15}$$

where $\bar{x}$ = arithmetic mean

$x_1, x_2, x_3, \ldots, x_n$ = readings taken

n = total number of readings

1.5.2 Deviation

It is the departure of a given reading from the arithmetic mean of the group of readings. If the deviation of the first reading, x_1, is called d_1, and that of the second reading, x_2, is called d_2, and so on, then the deviations from the mean can be expressed as

$$d_1 = x_1 - \bar{x},\ d_2 = x_2 - \bar{x},$$

Similarly, $d_n = x_n - \bar{x}$ (1.16)

The deviation may have a positive or negative value. The algebraic sum of all the deviations must be zero.

Average Deviation It may be defined as the sum of the absolute values of the deviations divided by the number of readings. The absolute value of the dimensions is the value without respect to sign. Average deviation may be expressed as

$$D_{av} = \frac{|d_1| + |d_2| + |d_3| + \ldots + |d_n|}{n}$$

or, $$D_{av} = \frac{\Sigma\,|\,d\,|}{n} \tag{1.17}$$

where, D_{av} = average deviation

$|d_1| + |d_2| + \ldots$ = absolute values of deviations

n = total number of readings

The average deviation is an indication of the precision of the instruments used in making the measurements. Highly precise instruments will yield a low average deviation between readings.

Standard Deviation The standard deviation of an infinite number of data is the square root of the sum of all the individual deviations squared, divided by the number of readings. It may be expressed as

$$\sigma = \frac{\sqrt{d_1^2 + d_2^2 + d_3^2 + \ldots + d_n^2}}{n} \quad \text{or,} \quad \sigma = \frac{\sqrt{\Sigma d^2}}{n} \tag{1.18}$$

where σ = standard deviation

The standard deviation is also known as the root mean square deviation and is the most important factor in the statistical analysis of measurement data. Reduction of this quantity effectively means improvement in measurement.

SELF-CHECK QUIZ

A. Tick (✓) the appropriate answer:-

1. A variable-manipulation element
   - (a) manipulates the signal to perform the intended task
   - (b) converts the output signals into a more suitable variable
   - (c) receives energy from the measured medium
   - (d) none of the these
2. A data-representation element
   - (a) transmits data from one element to the other
   - (b) performs translation functions
   - (c) manipulates the signal
   - (d) none of these
3. Precision is the
   - (a) degree of exactness
   - (b) closeness of agreement among a number of consecutive measurements
   - (c) ability to respond to true value of a measured variable
   - (d) none of the above

B. Fill-up the blanks:-

1. Calibration is the process of ____________________ by ____________________ of the correct value of each scale reading on a meter.
2. Static errors are generally of three types, given as (a) ________________________ (b) ________________ and (c) ______________________.
3. The average deviation is an ________________________ of the instruments.

REVIEW QUESTIONS

1. Differentiate between accuracy and precision.
2. Draw the block diagram of an instrument system and explain the functions of different functional elements. Make the block diagram showing the functional elements of a pressure gauge.
3. Define the following terms:
   - (a) repeatability
   - (b) rangeability
   - (c) reproducibility
   - (d) sensitivity
   - (e) speed of response
   - (f) lag
4. What are the different types of static errors? Explain each of them.
5. List the different sources of errors.
6. What are instrumental and environmental errors? How can they be avoided?

Part II
Electrical and Electronic Measurements

2

Units and Standards of Measurements

2.1 INTRODUCTION

Units and standards of measurements are important factors for monitoring and control of industrial parameters. The quality of an industrial product depends on units of measurement that are reliable and accurate. Also, accurate measurement standards are essential in industrial applications. A considerable number of units and standards have been used in industrial environment at various times. However, some systems of units and standards have been widely accepted by various industries throughout the world. In this chapter, various types of units and standards of measurements are discussed.

2.2 UNITS OF MEASUREMENT

The physical quantities must be defined, both in kinds and magnitude, to ensure precise technical communication about the results of measurement and perform calculations. A unit of measurement may be defined as the standard measure of each kind of physical quantity, and the number of the measure (also called *numerical ratio* or *numerical multiplier*) is given as the number of times the unit occurs in any given amount of the same quantity. Thus, the magnitude of a physical quantity may be written as

$$\text{Physical quantity} = \text{Numerical Ratio} \times \text{Measurement Unit} \qquad (2.1)$$

A physical quantity is always defined by the measurement unit. The numerical ratio has no physical meaning without the unit. A large number of systems of measurement units have been used at various times during human history. Some systems of units are of only historical interest, some are of value in theoretical discussions and some others have been employed in measurements in actual experimental work. Different measurement units have been found acceptable in different countries; however, there are some systems of measurement units which have been accepted throughout the world. With the development of science and growth of measurement technology discipline, efforts were made to standardize terms so that instrumentation professionals could effectively communicate among themselves and with specialists in other disciplines. It is, thus, essential to acquaint ourselves with important and commonly used systems of measurement units.

2.2.1 Fundamental and Derived Units

The following two kinds of units are used in science and engineering:

- Fundamental units (or quantities)
- Derived units (or quantities)

The measurement of a quantity means the comparison of the quantity with a standard of the same kind of quantity. The magnitude of the quantity being measured can be expressed in terms of the chosen unit and a numerical multiplier. But, it is not possible to have a series of standards for each quantity, and also the unit of a quantity cannot be freely chosen because physical quantities are not independent of each other. Instead, they are related by some physical equation.

If there are M kinds of quantities to be evaluated and N independent physical equations expressing relationships between them, the sizes of units of only $(M - N)$ of the quantities can be chosen, and then the sizes of units of the remaining N quantities can be derived with the help of N physical equations so that the numerical multipliers are usually unity. The $(M - N)$ quantities, which are independently chosen, are called *fundamental quantities*. The remaining N units are called *derived quantities*. The units of fundamental quantities are called *fundamental units* and that of derived quantities are called *derived units*.

In mechanics, the fundamental units are measures of length, mass and time. The sizes of the fundamental units, whether foot or metre, pound or kilogram, second or hour, are arbitrary and can be selected to fit a certain set of circumstances. Since length, mass and time are fundamental to most other physical quantities besides those in mechanics, they are called *primary fundamental units*. Measures of certain physical quantities in the thermal, electrical and illumination disciplines are also represented by fundamental units. These units are used only when these particular classes are involved, and they are therefore defined as *auxiliary fundamental units*.

All other units, which can be expressed in terms of fundamental units, are called *derived units*. Every derived unit originates from some physical law defining that unit. For example, the volume of a substance is proportional to its length (l), breadth (b) and height (h), or $V = l \times b \times h$. If the metre has been chosen as the unit of length, then the volume of a substance of 4 m by 5 m by 6 m is 120 m^3. Note that the number of measures are multiplied ($4 \times 5 \times 6$) as well as the units ($\text{m} \times \text{m} \times \text{m} = \text{m}^3$). The derived unit of volume (V) is then the cube of metre (m^3).

2.2.2 Absolute Units

A system in which the various units of measurement are all expressed in terms of fundamental units is called *absolute units*. An absolute measurement does not compare the measured quantity with arbitrary units of the same kind, but is made in terms of some of fundamental units. The committee of the British Association of Electrical Units and Standards formulated the absolute system of units in 1863 and decided on the centimetre and gram as the fundamental units of length and mass. They decided that the units should not be defined by a series of master standards, each defining one quantity in the way in which the units of length, mass and time are defined. Instead, some natural law that expresses the relation between the quantity concerned and the fundamental quantities of length, mass and time, for which internationally accepted standards have already been established, should define each electrical unit.

2.2.3 CGS System of Units

The Centimetre-Gram-Second (CGS) system of units was the most commonly used system of units in electrical works before the MKS system of units came in existence. This system was developed from the absolute system of units formulated by the committee of the British Association of Electrical Units and Standards. Complication arose when the CGS system was extended to electric and magnetic measurements because of the need to introduce at least one more unit in the system. The following two parallel systems of units were established:

- CGS Electrostatic Systems
- CGS Electromagnetic Systems

In the CGS Electrostatic system, the unit of electric charge was derived from the centimetre, gram and second by assigning the value 1 to the permittivity of free space in Coulomb's law for the force between electric charges and is given as

$$F = \frac{Q_1 Q_2}{\varepsilon r^2} \tag{2.2}$$

where F = force between the charge, expressed in g cm/s = dyne
Q_1, Q_2 = equal point charges expressed in state coulomb
ε = Permittivity of the medium
r = distance (separation) between the charges expressed in centimetre

In the CGS Electromagnetic system, the basic units are the same and the unit of magnetic pole strength is derived from the centimetre, gram and second by assigning the value 1 to the permeability of free space in the inverse square formula for the force between magnetic poles. It is given as

$$F = \frac{2\mu I^2 b}{a} \tag{2.3}$$

where F = force between two current-carrying conductors expressed in dyne
μ = permeability of the medium
I = current flowing in the conductor expressed in ampere
B = length of current carrying conductor expressed in cm
A = distance of separation of conductors in cm

Disadvantages of the CGS system of Units

- There are two system of units; CGS electrostatic and CGS electromagnetic for fundamental theoretical work and a third (practical units) for practical engineering work.
- There are two sets of dimensional equations for the same quantity.

2.2.4 MKS System of Units

The Metre-Kilogram-Second (MKS) system of units was first suggested by the Italian physicist Giorgi in 1901. He pointed out that the practical units of current, voltage, energy and power, used by electrical engineers, were compatible with the metre-kilogram-second system. He suggested that the metric system be expanded into a coherent system of units by including the practical electrical units. The Giorgi system, adopted by many countries in 1935, came to be known as the MKSA system of units in which the ampere was selected as the fourth basic unit. This system was adopted by the International Electrical Commission (IEC) at its meeting in 1938. In order to connect the electrical and mechanical quantities, the fourth fundamental quantity, permeability, was introduced.

Advantages of the MKS system of Units

- Its units are identical with the practical units.
- Its units are the same, whether built up from the electrostatic or electromagnetic theory.
- The cumbersome conversions necessary to relate the units of the electrostatic and electromagnetic CGS systems to those of the practical system are avoided.

2.2.5 International System (SI) of Units

At the Eleventh General Conference on Weights and Measures, a more comprehensive system was adopted in 1954 and designated in 1960 by an international agreement as the *System International d'Unites* (SI) for worldwide standardization. In the SI system, six basic units are used, namely, the metre (m), kilogram (kg), second (s), and ampere (A) of the MKSA system and, in addition, the kelvin (K) and the candela (cd) as the units of temperature and luminous intensity, respectively. In addition, there are three supplementary units, namely, the radion (rad) for plane angle, steradian (sr) for solid angle and mole (mol) for quantity of substance. Everything else falls into the category of derived or defined units, meaning defined in terms of the six basic and three supplementary units. The six basic and three fundamental units are listed in Table 2.1.

Table 2.1 *Fundamental, Supplementary and Derived SI Units*

Quantity	*Unit*	*Unit Symbol*
Fundamental (Basic) Units		
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric Current	Ampere	A

Quantity	*Unit*	*Unit Symbol*
Thermodynamic Temperature	Kelvin	K
Luminous Intensity	Candela	cd
Supplementary Units		
Plane Angle	Radian	rad
Solid Angle	Steradian	sr
Quantity of Substance	Mole	mol
Derived Units		
Area	Square metre	m^2
Volume	Cubic metre	m^3
Velocity	Metre per second	m/s
Angular Velocity	Radian per second	rad/s
Frequency	Hertz	Hz
Density	Kilogram per cubic metre	kg/m^3
Acceleration	Metre per second squared	m/s^2
Angular Acceleration	Radian per second squared	rad/s^2
Force	Newton	N ($kg\ m/s^2$)
Pressure, Stress	Newton per square metre	N/m^2
Power	Watt	W (J/s)
Work, Energy	Joule	J (Nm)
Potential difference, Electromotive force	Volt	V (W/A)
Electric Capacitance	Farad	F (A s/V)
Electric Resistance	Ohm	Ω (V/A)
Magnetic Flux	Weber	Wb (v s)
Inductance	Henry	H (V s/A)
Electric Field strength	Volt per metre	V/m
Magnetic Field strength	Ampere per metre	A/m
Luminous Flux	Lumen	lm (cd sr)
Luminance, Brightness	Candela per square metre	cd/m^2
Illumination	Lux	l × (lm/m^2)

2.2.6 English Systems of Units

The English system of units uses the Foot-Pound-Second (FPS) as the three fundamental units of length, mass and time. This system of units has been historically employed in the United Kingdom and United States. Starting with these fundamental units, the mechanical units can be derived. The conversion between SI, CGS and FPS units is shown in Table 2.2.

Table 2.2 *Conversion Between SI, CGS and FPS Units*

Quantity	*SI Units*	*CGS Units*	*FPS Units*
Length	1 metre	100 centimetres	3.28084 feet
Mass	1 kilogram	1000 grams	0.0685 slugs
Time	1 second	1 second	1 second
Force	1 Newton	10^5 dynes	0.2248 pounds
Energy	1 joule	10^7 ergs	0.7376 ft-lb
Pressure	1 Pascal	10 dyne/cm^2	1.45×10^{-4} lb/in^2

Although the measures of length and weight are legacies of the Roman occupation of Britain, the inch (defined as one-tenth of the foot) has been determined at exactly 25.4 mm. Similarly, the measure for the pound (lb) has been determined as exactly 0.45359237 kg. These two figures allow all units in the English system to be converted into SI units.

2.3 STANDARDS OF MEASUREMENT

A standard of measurement is a physical representation of a unit of measurement. The term *standard* is applied to a piece of equipment having a known measure of physical quantity. It is used for obtaining the values of the physical properties of other equipment by comparison methods. A unit is realized by reference to an arbitrary material standard or to natural phenomena including physical and atomic constants. For example, the fundamental unit of mass in the SI system is the kilogram, defined as the mass of a cubic decimetre of water at its temperature of maximum density of 4°C. This unit of mass is represented by a material standard: the mass of the International Prototype Kilogram, consisting of a platinum—iridium alloy cylinder. This cylinder is preserved at the International Bureau of Weights and Measures at Sevres, near Paris, and is the material representation of the kilogram. Similar standards have been developed for other units of measurement, including standards for the fundamental units as well as for some of the derived mechanical and electrical units.

Therefore, standards are always arbitrary, whether they be the length of the 'foot' of a long-dead king, or the duration of a 'second'. Each standard is an invention of human beings to facilitate or make possible the measurements process. One of the most important responsibilities of a government is to set and maintain standards, thereby providing a commonly accepted basis for comparison.

2.3.1 Hierarchy of Standards

Just as there are fundamental and derived units of measurements, there is a hierarchy of standards of measurements as shown in Fig. 2.1, classified by their function and application in the following categories:

- International standards
- Primary standards
- Secondary standards
- Working standards

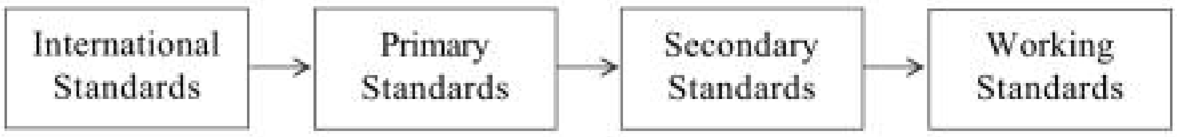


Fig. 2.1 *Hierarchy of Standards*

The *International standards* represent certain units of measurement which are closest to the possible accuracy attainable with present-day technological and scientific methods. They are defined on the basis of international agreements. International standards are regularly evaluated and checked against absolute measurements in terms of the fundamental units. International standards are maintained at the International Bureau of Weights and Measures and are not available to the ordinary user of measuring instruments for purposes of comparison or calibration.

The *primary (or basic) standards* represent the fundamental units and some of the derived mechanical and electrical units. One of the main functions of primary standards is the verification and calibration of secondary standards. They are maintained by national standard laboratories or stored in a government vault in different parts of the world. They are independently calibrated by absolute measurements at each of the national laboratories. The results of these measurements are compared against each other, leading to a world average figure for the primary standard. The National Bureau of Standards (NBS) in Washington is responsible for maintenance of the primary standards in North America. Other national laboratories include the National Physical Laboratory (NPL) in Great Britain and, the oldest in the world, the Physikalisch-Technische Reichsanstalt in Germany. Primary standards are the ultimate authority against which secondary standards are compared. They are not available for use outside the national laboratories.

The *secondary standards* are the basic reference standards used in industrial-measurement laboratories. These standards are maintained by the particular involved industry and are checked locally against other reference standards in the area. The industrial laboratories are entirely responsible for maintenance and calibration of the secondary standards. Secondary standards are normally sent to the national standards laboratories on a regular basis for their calibration and comparison against primary standards after which they are sent back to the industrial user with a certification of their measured value in terms of the primary standard.

The *working standards* are the principal tools of a measurement laboratory. They are used to check and calibrate general laboratory instruments for accuracy and performance or to perform comparison measurements in industrial applications. The working standards may be less accurate and less expensive.

2.3.2 IEEE Standards

The Institute of Electrical and Electronics Engineers (IEEE) is an engineering society, which has its headquarters in New York City of USA. It maintains standard procedures, nomenclature, definitions, etc., and is keeps updated information. These standards are not physical items that are available for comparison and checking of secondary standards. A large group of the IEEE standards is the standard test methods for testing and evaluating various measurement systems and components. Many of the IEEE standards have been adopted by other agencies as standards for their organization.

The IEEE standard specifies and addresses laboratory test equipment such as an oscilloscope about the controls, functions, etc., so that an oscilloscope operator does not have to re-educate himself for each oscilloscope he uses of a different make. Otherwise, it becomes difficult for an operator to use a laboratory test equipment when each manufacturer adopts a different arrangement of knobs and functions and, worst of all, different names for the same function.

IEEE 488 is one of the important IEEE standards used for digital electronic interface for advanced (programmable) instrumentation for test and other equipment. Standardizing the interface between test equipment makes it possible to interface various pieces of laboratory test equipment, regardless of manufacture, to create sophisticated automatic test-equipment system.

There are various IEEE standards concerning safety of electrical wiring for power plants, industrial buildings, process industries, etc. Standard voltages, current ratings, etc., are specified so that components may be interchanged without damage or danger. Standard schematic and logic symbols are defined so that all engineers can understand engineering drawings.

2.3.3 Standard Prefixes

It is necessary to abbreviate large and small numbers to take care of the wide variation of variable magnitudes that occur in industry. Scientific notation allows the expression of such numbers through powers of 10. A set of standard metric prefixes has been adopted by the Institute of Electrical and Electronic Engineers (IEEE) (Standard No. 268 A) to express these powers of 10, which are employed to simplify the expression of large and small numbers as shown in Table 2.3.

Table 2.3 *Standard Prefixes*

Multiple	*SI Prefix*	*Symbol*
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

2.4 TIME STANDARDS AND AUTOMATIC FREQUENCY

A measure of time is a phenomenon that repeats itself, and the measurement is done by counting of repetitions. An example of time standard is the rotation of the earth on its axis that determines the length of the day, which has been in use for long. Time defined in terms of the earth's orbital motion is called Ephemeris Time (ET), and time defined in terms of the rotation of the earth is called Universal time (UT). Both UT and ET are determined by astronomical observation. A good secondary terrestrial clock calibration by astronomical standards is needed for determination of UT that extends over several weeks and ET, which extends for several years. A quartz clock based on electrically sustained natural periodic vibration of a quartz wafer serves as a secondary time standard. These clocks have a maximum error of 0.02 seconds per year. Determination of frequency is the most common of time standards.

The measurement of time has two different aspects: (a) scientific, and (b) civil. In most scientific work, it is required to know how long an event lasts. Thus, any time standard must be able to answer questions such as 'What time is it?' and 'How long does it last?', or 'What is its frequency?'

Atomic clocks have been developed using periodic atomic vibrations as a standard. Such clocks meet better time standards. The transition between two energy levels, E_1 and E_2 of an atom is accompanied by the absorption (or emission) of radiation given by the equation

$$v = \frac{(E_2 - E_1)}{h} \tag{2.4}$$

where v = frequency of emission
h = Planck's constant = 6.636×10^{-34} Joules-second
E_1 and E_2 = two energy levels

The frequency of emission v depends on the internal structure of an atom. Since frequency is the inverse of time interval, time can be calibrated in terms of frequency. The atomic clock is constructed on the above principle. The first atomic clock was constructed based on the cesium atom. The International Committee of Weights and Measures defines the second in terms of the frequency of cesium transitions, assigning a value of 9,192,631,770 Hz to the hyperfine transitions of the cesium atom unaffected by external fields. If two cesium clocks are operated at one precision, and if there are no other sources of error, the clocks will differ by only 1 second in 5,000 years.

SELF-CHECK QUIZ

A. Tick (✓) the appropriate answer:-

1. The measurement of a quantity means
   - (a) the comparison of the quantity with a standard of the same kind of quantity
   - (b) the comparison of the quantity with a standard of a different kind of quantity

(c) both the above

(d) none of the above

2. The fundamental units in mechanics are measures of

   (a) length (c) time

   (b) mass (d) all of the above

3. Derived units

   (a) are expressed in terms of fundamental units

   (b) originate from physical law

   (c) are recognized by their dimensions

   (d) all of the above

4. In CGS electrostatic systems of units, the fourth unit, in addition to three fundamental units, is

   (a) permittivity (b) permeability

   (c) distance between two charges (d) length

5. In CGS electromagnetic systems of units, the fourth unit, in addition to the three fundamental units, is

   (a) permittivity (b) permeability

   (c) time (d) mass

6. The base units in the SI system are

   (a) metre, kilogram, second, ampere, kelvin, candela, mole

   (b) metre, kilogram, second, ampere, kelvin, candela

   (c) metre, kilogram, second, ampere, kelvin

   (d) metre, kilogram, second, ampere

7. The English system of units uses

   (a) metre, kilogram, second (b) foot, pound, second

   (c) meter, pound, second (d) foot, kilogram, second

B. Fill-up the blanks:-

1. The MKS system was first suggested by ______________________________.
2. In SI units, in addition to the MKS units, the two more units used are
   (a) __________________ , and (b) ___________________.

C. State True/False:-

1. A standard of measurement is a physical representation of a unit of measurement.
2. The average deviation is also known as root mean square deviation.
3. Measurement is a comparison of a given unknown quantity with one of its predetermined standard values adopted as a unit.
4. A given instrument cannot involve the same element in any number or combination.
5. Backlash is a lost motion or free play, which is inherent in mechanical elements.

REVIEW QUESTIONS

1. Differentiate between accuracy and precision.
2. Draw the block diagram of an instrument system and explain the function of different functional elements. Make the block diagram showing the functional elements of a pressure gauge.
3. Define the following terms:
   (a) Repeatability
   (b) Rangeability
   (c) Reproducibility
   (d) Sensitivity
   (e) Speed of response
   (f) Lag
   (g) Units
   (h) Absolute Units
   (i) Fundamental Units
   (j) Derived Units
4. What are the different types of static errors? Explain each of them.
5. List the different sources of errors.
6. What are instrumental and environmental errors? How can they be avoided?
7. What is the difference between a primary and secondary standard?
8. What is IEEE standard? How do these standards differ from those maintained by national standards laboratories?
9. Discuss the two systems of CGS units and find out the relationship among the two systems.
10. Distinguish between the following:
   (a) International Standards
   (b) Primary Standards
   (b) Secondary Standards
   (d) Working Standards

3

Electrical Measuring Instruments

3.1 INTRODUCTION

Electrical measurements of different parameters like current, voltage, power, energy, etc. are most essential in any industry. These are among the oldest of all measurements. The measurement of current, voltage or power is required to study the behaviour of an electrical equipment or an electrical circuit, under certain load conditions. In this chapter, the construction, operating principles, advantages and disadvantages of different types of electrical measuring instruments have been discussed.

3.2 CLASSIFICATION

The various electrical instruments may be broadly divided into two categories:

3.2.1 Absolute Instruments

Absolute instruments are those which give the value of the electrical quantity to be measured, in terms of the constants of the instruments and their deflection only, e.g. tangent galvanometer, Rayleigh current balance, etc. These instruments are rarely used except in standard laboratories.

3.2.2 Secondary Instruments

Secondary instruments are those which have been precalibrated by comparison with an absolute instrument. The value of the electrical quantity to be measured in these instruments can be determined from the deflection of the instrument. Without calibration of such an instrument, the deflection is meaningless. Instruments of this types are widely used.

Secondary type of measuring instruments have been classified in the following three categories:

(a) Indicating Instruments Indicating instruments are those which indicate the instantaneous value of the electrical quantity being measured, at the time at which it is being measured. Their indications are given by pointers moving over calibrated dials (or scales), e.g. ammeters, voltmeters and wattmeters.

(b) Recording Instruments Recording instruments are those which give a continuous record of variations of the electrical quantity over a selected period of time. The moving system of the instrument carries an inked pen which rests tightly on a graph chart.

(c) Integrating Instruments Integrating instruments are those which measure and register, by a set of dials and pointers, either the total quantity of electricity (in ampere-hours) or the total amount of electrical energy (in watt-hours or kilowatt-hours) supplied to a circuit over a period of time, e.g. ampere-hour meters, watt-hour meters, energy meters, etc.

3.3 ESSENTIALS OF INDICATING INSTRUMENTS

In most indicating instruments, three distinct forces are essential for the satisfactory indication of the pointer on a dial. These forces are:

(i) a deflecting (or operating) torque
(ii) a controlling (or restoring) torque
(iii) a damping torque

3.3.1 Deflecting Torque (T_d)

It is the torque which deflects the pointer on a calibrated scale according to the electrical quantity passing through the instrument. This deflecting torque causes the moving system, and hence the pointer attached to it, to move from its zero position, i.e. its position when the instrument is disconnected from the supply.

3.3.2 Controlling Torque (T_c)

It is the torque which controls the movement of the pointer on a particular scale according to the quantity of electricity passing through it. The controlling forces are required to control the deflection or rotation and bring the pointer to zero position when there is no force, or stop the rotation of the disc when there is no power. Without such a torque, the pointer would swing over to the maximum deflected position irrespective of the magnitude of current or voltage being measured.

In indicating instruments, the controlling torque, also called the restoring or balancing torque, is obtained by two methods which are discussed below.

Spring Control In the spring control method, a hair-spring, usually of phosphor-bronze, attached to the moving system is used. Figure 3.1 shows a spring control arrangement in which a spring B is attached to a pointer A.

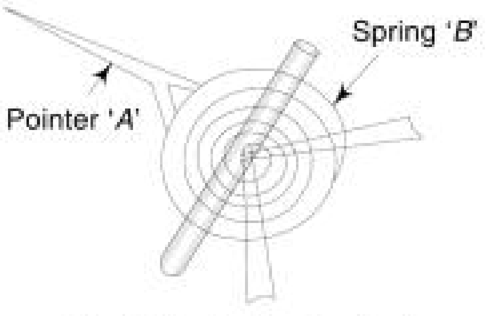


Fig. 3.1 *Spring Control*

With the deflection of the pointer, the spring is twisted in the opposite direction. This twist in the spring produces a restoring torque which is directly proportional to the angle of deflection of the moving system. The pointer comes to a position of rest (or equilibrium) when the deflecting torque (T_d) and controlling torque (T_c) are equal.

The controlling torque for a spring control is given by the empirical formula:

$$T_c = \frac{Ebt^3}{12\,L}\,\theta \tag{3.1}$$

where E = Young's modulus of material of spring, in kg/m^2
b = width of the spring, in m
t = thickness of the spring, in m
θ = deflection, in radian
L = total length of the spring, in m

For a particular spring, E, b, t and L are constant

$$\therefore \quad T_c = K\theta$$

where $$K = \frac{Ebt^3}{12\,L}$$

K is called the spring constant.

Thus, $T_c \propto \theta$

i.e., Controlling torque (T_c) $\propto$ Deflection (θ). (3.2)

To give a controlling torque which is directly proportional to the angle of deflection of the moving system, the number of turns of the spring should be fairly large so that the deformation per unit length is small. The stress in the spring must be limited to such a value that there is no permanent set. Springs are made of materials which are

(i) non-magnetic
(ii) not subjected to much fatigue
(iii) low in specific resistance
(iv) have low temperature coefficient of resistance

Gravity Control Gravity control is obtained by attaching a small weight to the moving system in such a way that it produces a restoring or controlling torque when the system is deflected (Figs 3.2 (a) and (b)).

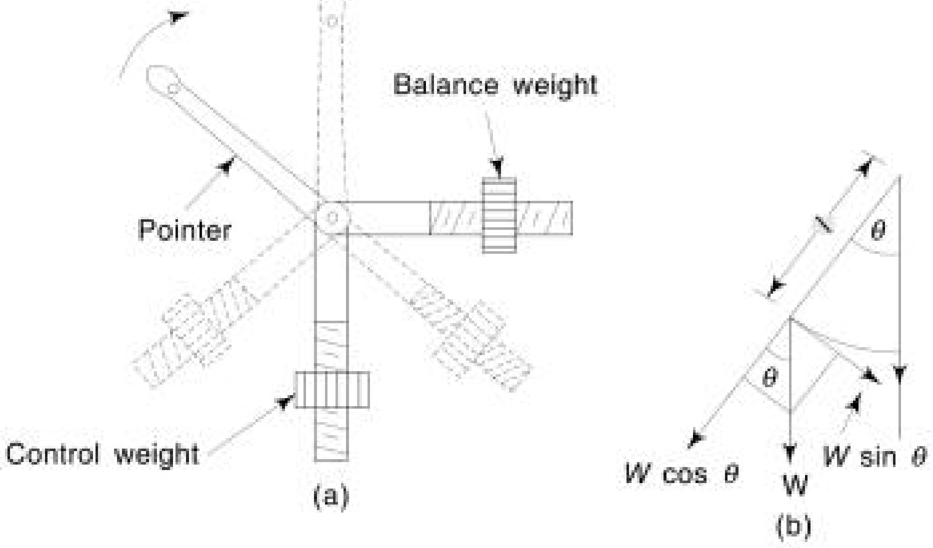


Fig. 3.2 *Gravity Control*

From Fig. 3.2 (b), the control torque will be:

$$T_c = Wl \sin \theta$$

where W = control weight

l = the distance from the axis of rotation of the moving part

θ = deflection

But W and l are constant,

$\therefore \quad T_c = K \sin \theta$

where $K = Wl$ = a constant

or $\quad T_c \propto \sin \theta \qquad (3.3)$

Thus, controlling torque in a gravity control system is proportional to the sine of the angle of deflection.

The degree of control is adjusted by screwing the weight up or down on the carrying system.

Advantages The advantages of the gravity control system, as compared to spring control, are given below:

(i) It is cheap.

(ii) It is unaffected by temperature.

(iii) It is not subjected to fatigue or distortion, with time.

Disadvantages The disadvantages of the gravity control system, as compared to spring control, are given below:

(i) It gives a cramped scale.

(ii) The instrument has to be kept vertical.

3.3.3 Damping Torque

It is the torque which avoids the vibration of the pointer on a particular range of scale. Such a damping or stabilizing force is necessary to bring the pointer to rest quickly, otherwise, due to inertia of the moving system, the pointer will oscillate about its final deflected position for quite some time before coming to rest in the steady position.

There are three types of damping:

Air-Friction Damping Air-friction damping uses either aluminium piston or vane, which is attached to or mounted on the moving system and moves in an air chamber at one end.

Fluid-Friction Damping In fluid-friction damping, a light vane (attached to the moving system) is dipped into a pot of damping oil. The fluid produces the necessary opposing (or damping) force to the vane. The vane should be completely submereged in the oil.

The disadvantage of this type of damping is that it can only be used in the vertical position.

Eddy-Current Damping Eddy-current damping uses a conducting material which moves in a magnetic field so as to cut through the lines of force, thus setting up eddy currents. Force always exists between the eddy current and magnetic field which is always opposite to the direction of motion. This is the most efficient type of damping and is largely used in permanent magnet moving coil instruments, hot wire instruments and induction type instruments.

3.4 TYPES OF ELECTRICAL INSTRUMENTS

Electrical measuring instruments may be classified as follows:

(i) moving-iron instruments
(ii) moving-coil instruments
(iii) hot-wire instruments
(iv) induction-type instruments
(v) electrostatic instruments.

3.5 MOVING-IRON INSTRUMENTS

Moving-iron instruments depend for their action upon the magnetic effect of current, and are widely used as indicating instruments. In this type of instrument, the coil is stationary and the deflection is caused by a soft-iron piece moving in the field produced by the coil.

There are two types of moving-iron instruments:

(i) Moving-vane (or attraction) type
(ii) Double-vane (or repulsion) type

3.5.1 Moving-Vane or Attraction Type

Working Principle The basic working principle of attraction-type moving-iron instruments is illustrated in Fig. 3.3 (a). In this system, when current flows through the coil, a magnetic field is produced at its centre. A soft-iron vane fixed to the spindle becomes magnetized and is pulled inside the coil, the force of attraction being proportional to the strength of the field inside the coil, which again is proportional to the strength of the current.

Moreover, with the reversal of current in the coil, the field inside the coil and the magnetization of the soft-iron vane are both reversed, causing the force of attraction to be in the same direction.

Construction and Working A sectional view of the actual instrument is shown in Fig. 3.3 (b). When the current to be measured is passed through the coil or solenoid C, a magnetic field is produced which attracts the eccentrically mounted disc or vane A inwards, thereby deflecting the pointer which moves over a calibrated scale.

Deflecting Torque In the attraction-type moving-iron instrument, the deflecting torque is due to the force of attraction between the field of the coil and the moving iron disc.

The magnetization of the iron disc is proportional to the field strength H. The force F pulling the disc inwards is proportional to the magnetization M of the disc and field strength H.

Therefore,

Deflecting torque $(T_d) \propto MH$

But, $M \propto H$

and $H \propto I$

$\therefore$ $T_d \propto I^2$ (3.4)

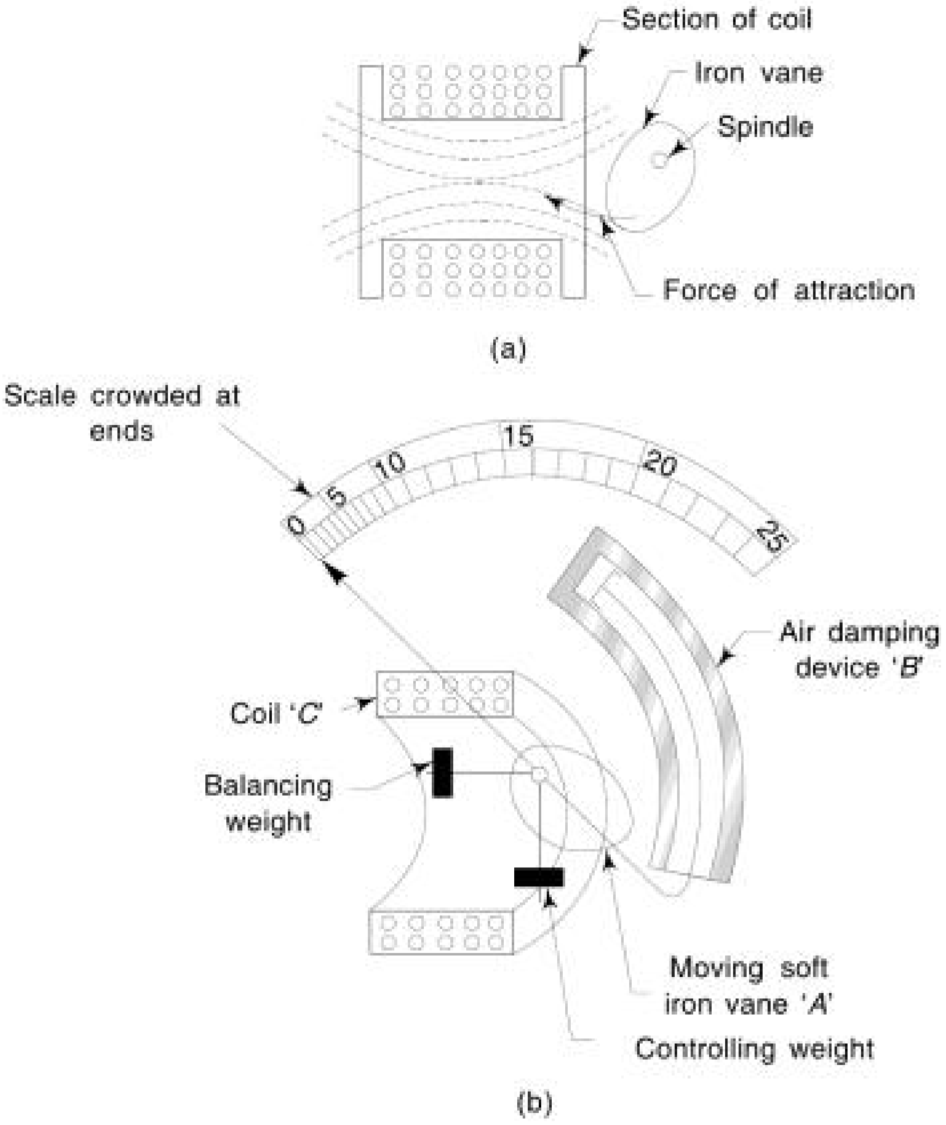


Fig. 3.3 *(a) Working Principle of Attraction-type Instrument, (b) Moving-Iron Attraction-type Meter*

Thus, the deflecting torque is proportional to the square of the current passing through the coil.

Controlling Torque In the above instrument the controlling torque is achieved by gravity control, but now spring control is used almost universally.

Damping Torque The damping of the moving system is obtained by air damping, in which a light aluminium piston moves freely inside the curved cylinder closed at one end. The resistance offered by air in escaping from the restricted space around the piston effectively damps out any oscillations.

3.5.2 Double-Vane or Repulsion Type

Construction Figure 3.4 shows a sectional view of a double-vane type moving-iron instrument. It consists of a fixed coil C inside which two soft-iron rods or vanes, A and B, are arranged parallel to one another and along the axis of the coil. One of these vanes, A, is fixed to the coil frame, while the other vane B is moving and is mounted on the spindle. The moving vane carries a pointer which moves over a calibrated scale.

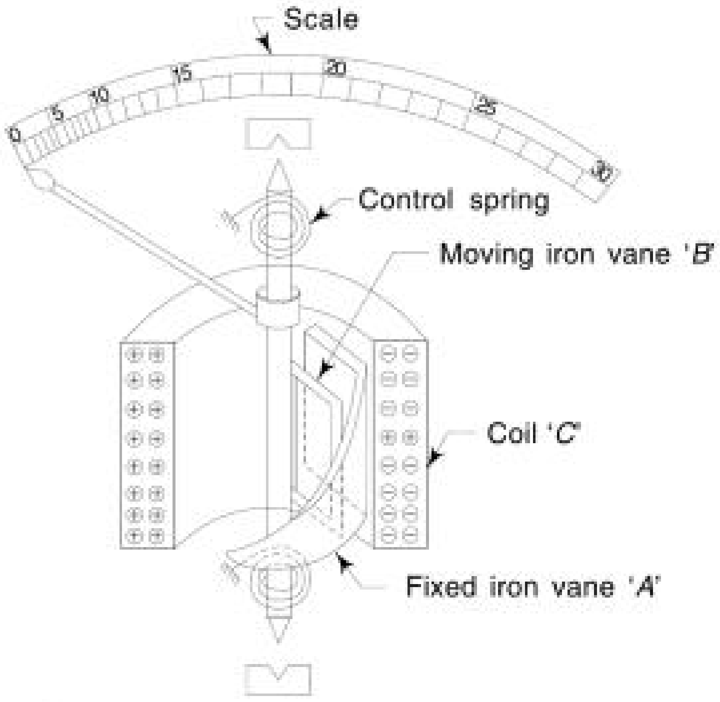


Fig. 3.4 *Moving-iron Repulsion-type Meter*

Working Principle When the current to be measured is passed through the fixed coil, it sets up its own magnetic field which magnetizes the two rods or vanes with the same polarity so that they repel one another, with the result that the pointer is deflected against the controlling torque of a spring or gravity. The force of repulsion is approximately proportional to the square of the current passing through the coil.

Moreover, a reversal in the direction of the current will affect both the vanes so that the force of repulsion will still be in the same direction. This property makes the meter suitable for use in both d.c. and a.c. circuits.

Deflecting Torque The deflecting torque is due to the force of repulsion between two similarly magnetized iron rods or vanes.

Therefore,

$$\text{Instantaneous torque} \propto \text{Repulsive force}$$

and Repulsive force $\propto$ Product of pole strengths m_1 & m_2 of two vanes.

Pole strength $\propto$ Magnetic field 'H' of the coil and Magnetic field 'H' $\propto$ current passing through the coil.

Therefore, the instantaneous torque, which is the deflecting torque, is given as:

$$\text{Instantaneous torque} \propto I^2$$

i.e.

$$T_d \propto I^2$$

Hence, deflecting torque is proportional to the square of the current. When used in an a.c. circuit, the instrument reads the r.m.s value of the electrical quantity.

Controlling Torque In this type of instrument, controlling torque is obtained either with a spring or by gravity. In Fig. 3.4 a spring has been used for the controlling torque.

Damping Torque In this type of instrument, pneumatic type damping is used. Eddy currents cannot be employed because the presence of a permanent magnet, required for such a purpose, would affect the deflection and hence the reading of the instrument.

As the deflection torque, in both attraction and repulsion-type moving-iron instruments, is proportional to the square of the current, the scale is crowded (not uniform) at the beginning. It is more so with the gravity control as the controlling torque is proportional to the sine of the angle of deflection, i.e. sine θ. This is rectified to some extent by making the moving vanes of a suitable shape.

3.5.3 Advantages of Moving-Iron Instruments

Following are the advantages of moving-iron instruments:

(i) Cheap, robust and give reliable service.
(ii) Usable in both a.c. and d.c. circuits.

3.5.4 Disadvantages and Limitations of Moving-Iron Instruments

Following are the disadvantages of moving-iron instruments:

(i) Have non-linear scale.
(ii) Cannot be calibrated with a high degree of precision for d.c. on account of the affect of hysteresis in the iron vanes.
(iii) Deflection of up to 240° only may be obtained with this instrument
(iv) The instrument will always have to be put in the vertical position if it uses gravity control.

3.5.5 Errors with Moving-Iron Instruments

Following are the errors of moving-iron instruments:

(i) Due to hysteresis when used in a.c. and d.c.
(ii) Due to stray fields when used both in a.c. and d.c.
(iii) Due to frequency variation when used in a.c.
(iv) Due to wave forms effect when used in a.c.

3.5.6 Applications of Moving-Iron Instruments

As an Ammeter It may be constructed for full-scale deflection of 0.1 to 30 A without the use of shunts or current transformers. To obtain full-scale deflection with currents less than 0.1 A, it requires a coil with a large number of fine wire turns, which results in an ammeter with a high impedance.

The range of the instruments, when used as an ammeter, can be extended by using a suitable shunt across its terminals. No problem arises during operation with d.c. but the division of current between instrument and shunt changes with the change in applied frequency while using a.c.

The multiplying power (N) of the shunt is given by

$$N = \frac{I}{i} = 1 + \frac{R}{R_s} \tag{3.5}$$

where, I = line current, in A

i = full-scale deflection of the meter, in A

R = resistance of the meter, in Ω

R_s = shunt resistance, in Ω

In case of d.c., the range of the instrument is extended by using a suitable shunt across the meter, as shown in Fig. 3.5.

According to Kirchhoff's voltage law,

$$I_g R_g = I_s R_s$$

or
$$R_s = \frac{R_g\ I_g}{I_s} \tag{3.6}$$

where, R_s = shunt reistance, in Ω

I_s = shunt current, in A

R_g = meter resistance, in Ω

I_g = meter full-scale deflection current, in A

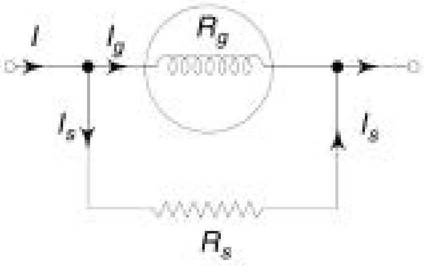


Fig. 3.5 *Extension of Range of Moving-iron Ammeter*

As a Voltmeter The moving-iron voltmeter is a fairly low impedance instrument, typically, 50 Ω/V for a 100 V instrument. The lowest full scale is of the order of 50 V.

The range of the instrument, when used as a voltmeter, can be extended by using a high non-inductive resistance R connected in series with it, as shown in Fig. 3.6. This series resistance is known as the "multiplier" when used in d.c. circuits.

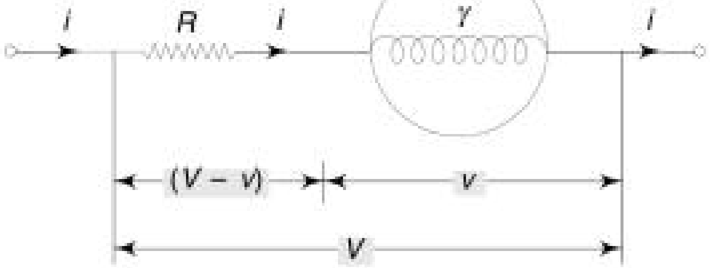


Fig. 3.6 *Extension of Range of Moving-iron Voltmeter*

Suppose, the range of the instrument is to be extended from v to V, so excess voltage $(V - v)$ will drop across R. If i is the full-scale deflection current of the instrument, then

$$i\,R = V - v$$

or,
$$R = \frac{V - v}{i} = \frac{V - ir}{i}$$

($\because$ $v = ir$, where r is the meter resistance)

or
$$R = \frac{V}{i} - r \tag{3.7}$$

Also,
$$i\,R = V - v$$

Now, dividing both sides by v

$$\frac{iR}{v} = \frac{V - v}{v}$$

or
$$\frac{iR}{v} = \frac{V}{v} - \frac{v}{v}$$

or,
$$\frac{iR}{ir} = \frac{V}{v} - 1$$

∴
$$\frac{V}{v} = 1 + \frac{R}{r} \tag{3.8}$$

where, $\frac{V}{v}$ is known as voltage magnification. Hence, the greater the value of R, the greater is the extension in the voltage range of the instrument.

3.6 MOVING–COIL INSTRUMENTS

There are two types of moving-coil instruments:

(i) Permanent magnet type
(ii) Dynamometer type

3.6.1 Permanent Magnet Moving-Coil Instrument

Working Principle The operation of a permanent magnet moving-coil instrument is based on the principle that when a current-carrying conductor is placed in a magnetic field, a force acts on the conductor, which tends to move it to one side and out of the field.

Construction It consists of a powerful U-shaped permanent magnet made of Alnico, and soft iron pole pieces bored out cylindrically, as shown in Fig. 3.7 (a). A soft iron core (cylinder) is fixed between the magnetic poles whose functions are (i) to make the field radial and uniform, and (ii) to decrease the reluctance of the air path between the poles and hence increase the magnetic flux. Surrounding the core is a rectangular coil of many turns wound on a light aluminium or copper frame, supported by delicate bearings. A light pointer fixed to the frame moves on the calibrated scale according to the amount of electricity passed through the coil. The aluminium frame provides not only support for the coil but also a damping torque by the eddy currents induced in it. The sides of the coil are free to move in the two air gaps between the poles and the core, as shown in Figs 3.7 (a) & (b).

Deflecting Torque When the current is passed through the coil, forces act upon both its sides and produce a deflecting torque (Fig. 3.8).

Let, B = flux density, in weber/m^2
l = length or depth of the coil, in m
b = breadth of the coil, in m
N = number of turns in the coil
I = current passing through the coil, in A

Now, the magnitude of the force experienced by each side of the coil is given as,

$$\text{Force} = BIl \text{ newton}$$

For N turns, the force on each side of the coil will be,

$$\text{Force} = N \times BIl \text{ newton}$$

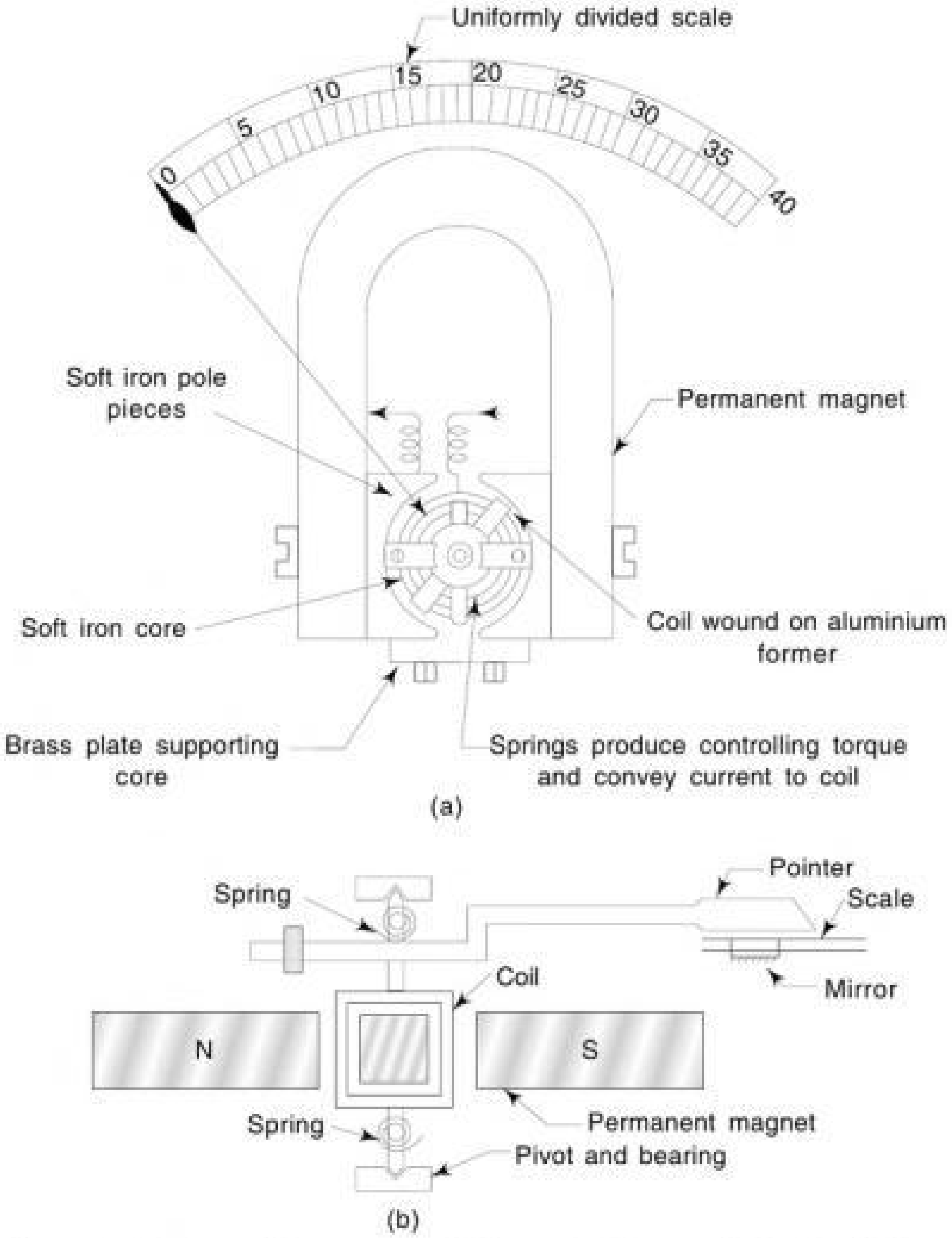


Fig. 3.7 *Moving-coil Instrument (a) Schematic Diagram (b) Sectional View*

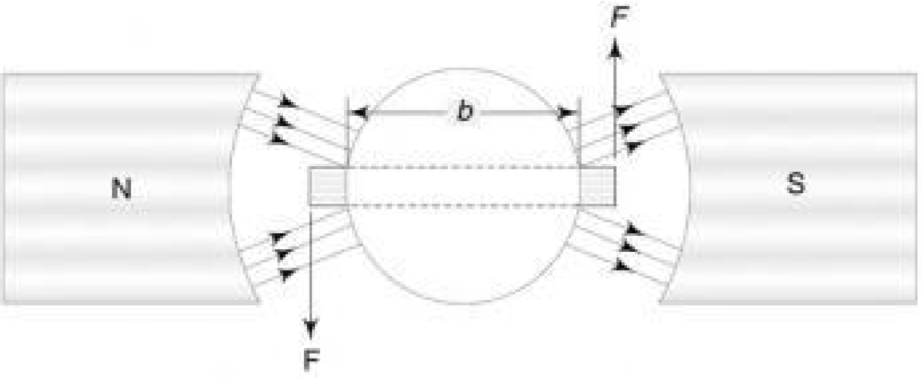


Fig. 3.8 *Force Producing a Deflecting Torque*

Now, Deflecting torque (T_d) = Force × Perpendicular distance

$\therefore \quad T_d = NBIl \times b$

or $\quad T_d = NBI\,(l \times b)$

But, $\quad l \times b = A$ = face area of the coil,

$\therefore \quad T_d = NBIAN\text{–}m \qquad (3.9)$

It is seen that, if B is constant, T_d is proportional to the current passing through the coil, i.e.

$T_d = KI$ (where K = NBA = constant)

or $\quad T_d \propto I$

Such instruments generally use spring control so that

Controlling torque $T_c \propto$ Deflection θ

Since, at final deflection position, $T_d = T_c$

$\therefore \quad T_d \propto \theta \propto NBIA$

or $\quad \theta \propto I$

Since the deflection is directly proportional to the current, such instruments have uniform scale.

Controlling Torque In this type of instrument, the controlling torque is provided by a spring, as shown in Fig. 3.7(b).

It is obtained by two phosphor-bronze hair springs, one above and the other below, which also serves the purpose of leading the current in and out of the coil. Two springs are spiralled in opposite directions to neutralize the effects of temperature change.

Damping Torque Damping is provided by currents induced in the aluminium frame on which the coil is wound. Damping is very effective in this type of instrument.

Advantages Following are the advantages of permanent magnet moving-coil instruments:

(i) Low power consumption.
(ii) Uniform scale extendable over an arc of 270° or so.
(iii) High torque/weight ratio.
(iv) No hysteresis loss.
(v) Very effective and efficient eddy current damping.
(vi) Not affected much by stray and magnetic fields due to strong operating field.

Disadvantages and Limitations Following are the disadvantages and limitations of the permanent magnet moving-coil instruments:

(i) Costlier compared to moving-iron instruments, due to delicate construction and accurate machining and assembly of various parts.
(ii) Some errors arise due to the ageing of control springs and the permanent magnet.
(iii) Use limited to d.c. only.
(iv) Scale length of meter can be increased from 120° and 240° or even 270° or 300° only.

Errors Following are the errors in permanent magnet moving-coil instruments:

(i) Due to friction of moving parts and temperature.

(ii) Due to weakening of the permanent magnet with the passage of time but can be eliminated by carefully ageing the magnet during its manufacture.

(iii) An account of thermoelectric emf when they are shunted for current measurement (this error can be minimized with a well-designed shunt).

Torque and Weight Ratio In order to reduce the load on the bearings and the friction torque, which is proportional to the pressure on the bearing surface, the weight of the moving parts should be as small as possible. The torque/weight ratio is influenced by the axis of the moving system being vertical or horizontal.

Applications The permanent-magnet moving-coil instrument may be applied in the following instruments:

As an Ammeter The range of the instrument, when used as an ammeter, can be increased by using a large number of turns in parallel with the instruments, as shown in Fig. 3.9 below:

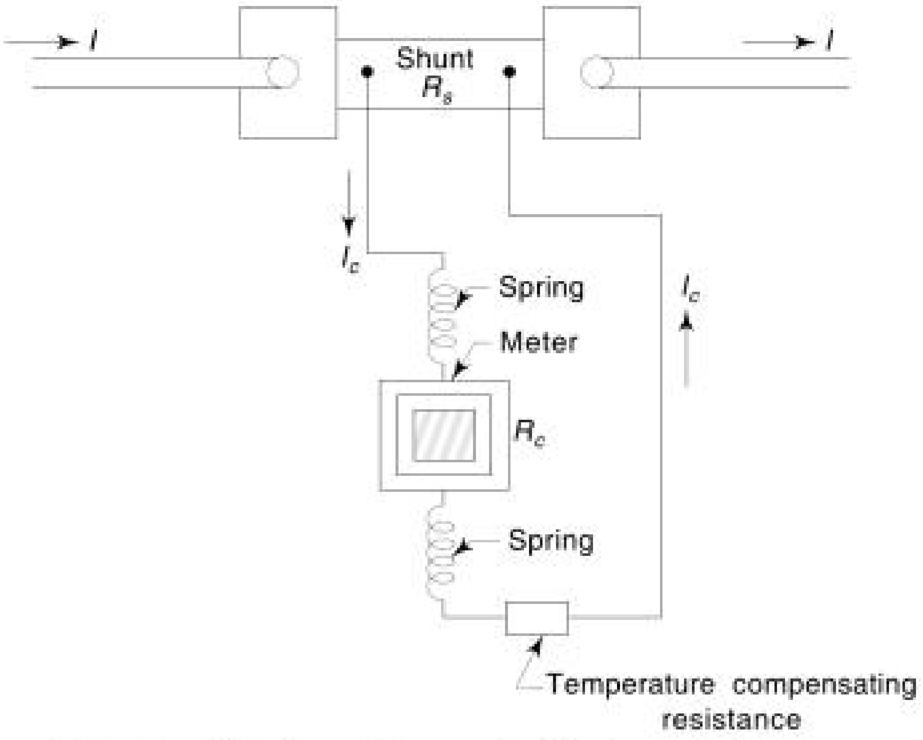


Fig. 3.9 *Extension of Range of a Moving-coil Ammeter*

Let, R_c = coil resistance, in Ω
I = line current, in A
R_s = shunt resistance, in Ω
I_c = full-scale deflection current of the instrument, in A
$I_s = (I - I_c)$ = shunt current, in A

Therefore, according to Kirchhoff's voltage law, from Fig. 3.9,

$$R_c \times I_c = R_s \times (I - I_c)$$

$$R_s = \frac{R_c \times I_c}{(I - I_c)}$$

or

$$R_s = \frac{R_c \times I_c}{I_s} \tag{3.10}$$

The multiplier power of shunt is given as:

$$\frac{I}{I_c} = \left(1 + \frac{R_c}{R_s}\right) \tag{3.11}$$

As a Voltmeter The range of this instrument, when used as a voltmeter, can be increased by using a high resistance in series with it, as shown in Fig. 3.10.

Let, I_g = full-scale deflection current of the instrument, in A.

R_g = Resistance of the instrument, in Ω

$v = R_g I_g$ = full-scale potential difference across the instrument, in volts

R = Series resistance required, in Ω

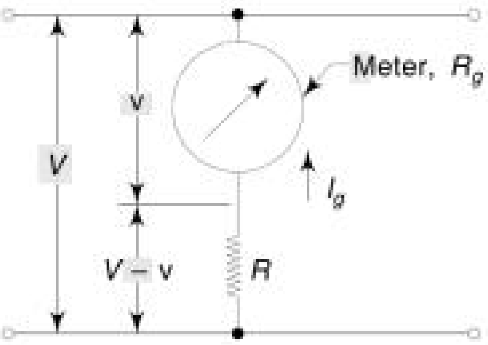


Fig. 3.10 *Extension of Range of a Moving-coil Voltmeter*

Therefore, voltage drop across R is given as:

$$V - v = I_g R \tag{3.12}$$

or

$$R = \frac{V - v}{I_g} \tag{3.13}$$

Dividing both sides of the Eq. (3.12) by v, we get

$$\frac{R \cdot I_g}{v} = \frac{V - v}{v}$$

or

$$\frac{R \cdot I_g}{R_g\, I_g} = \frac{V}{v} - 1$$

or,

$$\frac{V}{v} = \left(1 + \frac{R}{R_g}\right) \tag{3.14}$$

The Eq. (3.14) is known as the voltage multiplication of the instrument. It increases with increase in the series resistance R.

3.6.2 Dynamometer-Type (or Electrodynamic) Moving Coil Instrument

The difference between dynamometer type instruments and the permanent magnet type is that in the former the air gap flux is produced by electromagnet in the form of one or two fixed coils. The fixed coils carry the current to be measured, or current proportional to the voltage to be measured, and are connected in series or parallel to the moving coil. The coils, in general, are air-cored to avoid errors due to hysteresis, eddy currents and other errors when the instrument is used for a.c. measurement. Since the flux in this type of instrument is only about three to four percent of that of the permanent magnet type, the number of ampere-turns required on the moving coil is large. But the torque/weight ratio decreases due to a large number of ampere-turns. This instrument is used both for a.c. and d.c. measurements.

Construction Figure 3.11 shows a diagram of the dynamometer type moving-coil instrument. The different parts are discussed below.

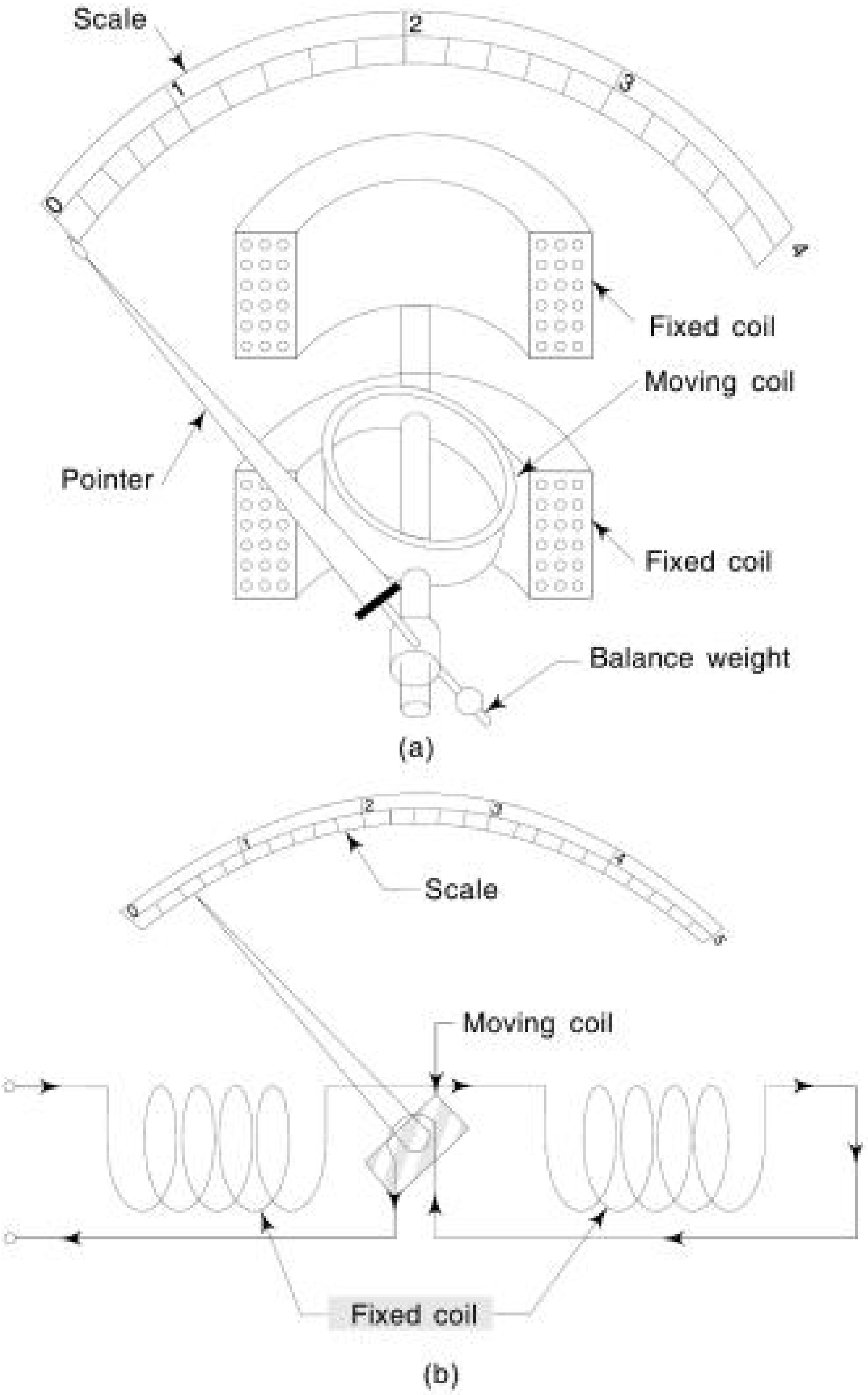


Fig. 3.11 *Dynamometer Instrument (a) Schematic Diagram (b) Connection Diagram*

Fixed Coils A field is produced by the fixed coil which is divided into two sections to give a uniform field near the centre. The fixed coils are wound with fine wire when used as a voltmeter and with heavy wire when used as an ammeter and wattmeter. The wire is stranded, when necessary, to reduce eddy current losses in conductors.

Moving Coil The moving coil is wound either as a self-sustaining coil or wound on a non-metallic former. A metallic former cannot be used due to eddy current loss. Both moving coils and fixed coils are air-cored.

Moving System The moving coil is mounted on an aluminium spindle which carries the counter weights and truss-type pointer (Fig. 3.11(a)).

Control System The controlling torque is provided by two control springs, which also act as leads to the moving coil.

Damping System This system provides for air-damping. Two light vanes are mounted on the spindle and move in a double sector shaped box.

Working Principle The operating principle of electrodynamic (or dynamometer type) instruments is the interaction between the currents in the moving coil, mounted on a shaft, and the fixed coils.

When the two coils are energized, their magnetic fields interact and the resulting torque tends to rotate the moving coil. Since there is no iron, the field strength is proportional to the current in the fixed coil and, therefore, the deflecting torque is proportional to the product of the currents in the fixed coil and the moving coil.

When used as a wattmeter, the fixed coil is the current coil and the moving coil is the pressure coil. Thus the current in the latter is proportional to the voltage applied. Hence, the deflecting torque is proportional to the product of voltage and current (that is, power). As the restoring (or controlling) torque, which is provided by spiral springs, is proportional to the deflection, it follows that the deflection is proportional to the power.

Deflecting Torque The deflecting torque for sinusoidal currents is given by

$$T_d = I_1 I_2 \cos\phi \, \frac{dm}{d\theta} \tag{3.15}$$

where, I_1 = the current in fixed coil, in A

I_2 = the current in moving coil, in A

ϕ = the phase angle between I_1 and I_2.

$\frac{dm}{d\theta}$ = the rate of change of mutual inductance between fixed and moving coils.

θ = the angle of deflection.

In a dynamometer-type instrument, the fixed and moving coils are connected in series and hence carry the same current and have zero phase angle.

Therefore, $I_1 = I_2 = I$ (let)

and $\phi = 0$

The above expression for T_d will become as $T_d = I^2 \dfrac{dm}{d\theta}$

But, the controlling torque is given as $T_c = \mathrm{K}\theta$

Where K is a constant of the instrument

Now, for balance $T_d = T_c$

Therefore, $I^2 \dfrac{dm}{d\theta} = \mathrm{K}\theta$

or

$$\theta = \frac{I^2}{\mathrm{K}} \frac{dm}{d\theta} \tag{3.16}$$

Thus, dynamometer-type instruments can be used in a.c. circuits, for which square law is necessary.

Advantages Since the coils are generally air-cored, such instruments are free from eddy current and hysteresis losses.

Disadvantages Although these instruments are useful for precise measurements on alternating current circuits, they compare unfavourably with the permanent magnet type due to the following disadvantages:

(i) The magnetic field strength obtained in these instruments, being small due to the absence of iron, a large number of ampere-turns are required on the moving coil in order to obtain the necessary deflecting torque. As a result, the moving system becomes heavy and power loss becomes high.

(ii) Torque/weight ratio being small, there will be serious friction errors as well as those due to internal heating.

(iii) Because the deflecting torque varies with the square of the current, the scale is not uniform.

(iv) Such instruments are more expensive than the other types.

(v) Such instruments have low sensitivity.

Errors The errors in dynamometer-type moving-coil instruments are of the following types:

(i) Frictional errors due to heavy moving parts.

(ii) Temperature errors due to internal heating.

(iii) Errors due to stray magnetic field.

Applications

As an Ammeter This type of instrument can be used to measure a low range current as well as a heavy amount of current. When it is used as an ammeter of low range (about 0.2A), the moving and fixed coils are connected in series, as shown in Fig. 3.12(a).

When this type of instrument is used to measure a heavy amount of current, the moving coil is usually connected in series with its swamping resistance, across a shunt, together with the fixed coils (Fig. 3.12(b)).

As a Voltmeter When this type of instrument is used as a voltmeter, the fixed and moving coils are joined in series along with a high resistance (Fig. 3.13).

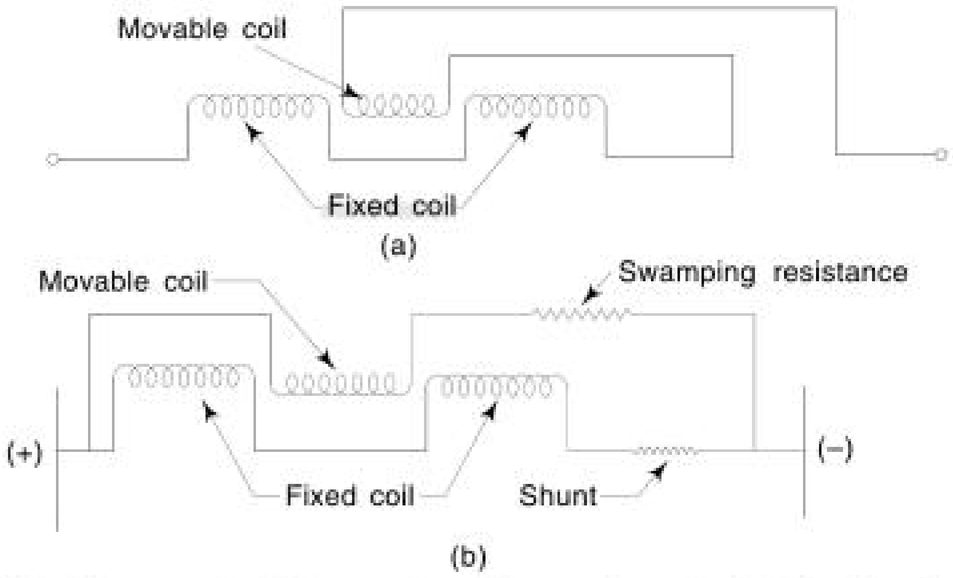


Fig. 3.12 *Dynamometer Instrument used as an Ammeter (a) For Low Range (b) For Large Range*

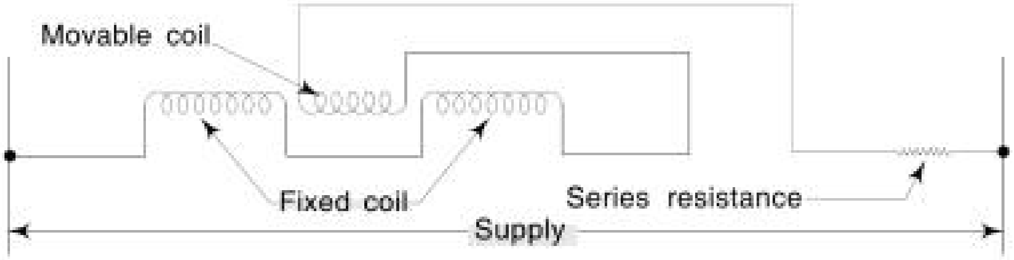


Fig. 3.13 *Dynamometer Instrument used as a Voltmeter*

The above circuit is used for the voltage range 50 to 500 V.

Dynamometer ammeters and voltmeters are not in common use, especially in direct current circuits.

As a Wattmeter The most important application of the dynamometer instrument as wattmeter has been discussed separately in this chapter.

3.7 HOT-WIRE INSTRUMENTS

These instruments utilize the principle of expansion of wire, heated due to the current being measured, passing through the wire.

3.7.1 Construction

It consists of a hot wire of platinum iridium (because it can withstand high temperatures of about 300°C without being oxidized), and about 0.2 mm in diameter. It is stretched between a fixed screw and a tension-adjusting screw (Fig. 3.14). A phosphor-bronze wire is attached to the hot wire and a fine silk thread is attached to the phosphor-bronze wire. This silk thread passes over a small pulley and is then attached to a spring which keeps the whole system taut. A light pointer is attached to the spindle upon which the pulley is mounted. Figure 3.14 shows the diagram of a hot-wire instrument.

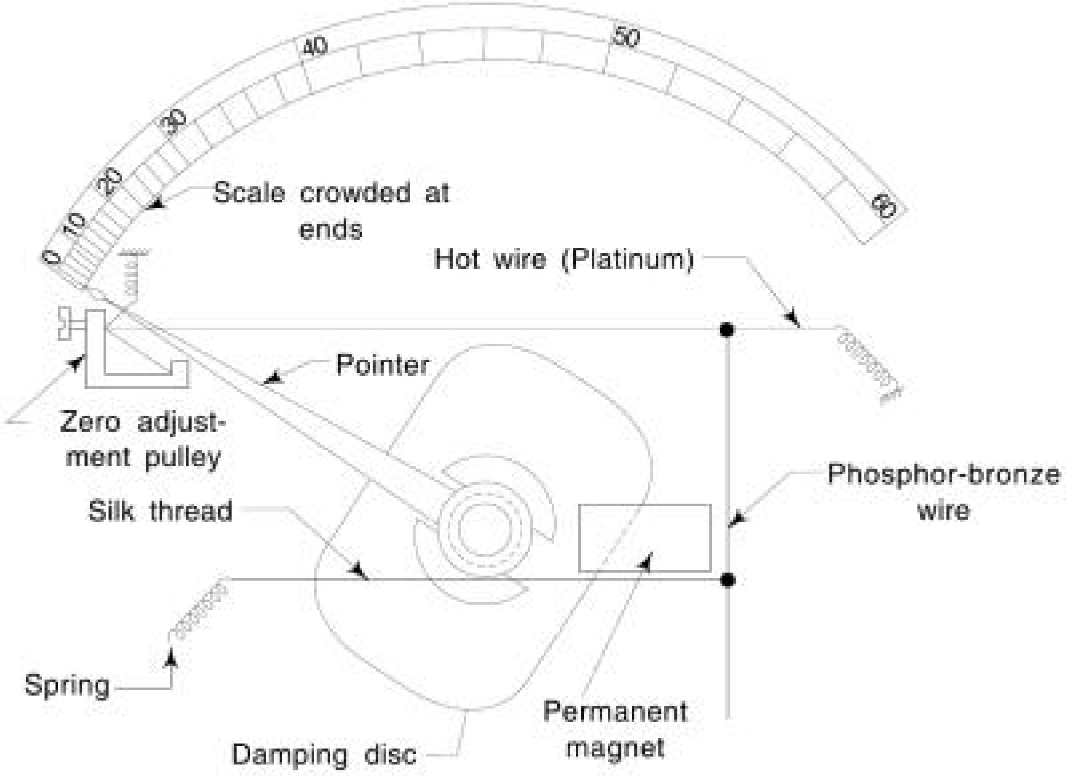


Fig. 3.14 *Hot-wire Instrument*

3.7.2 Working Principle

Working of the hot-wire instrument is based on the heating effect of electric currents. When the current to be measured passes through the hot wire, the wire gets heated and then expands. Since the wire is fixed between two points, it sags due to expansion which is magnified by the phosphor-bronze wire and silk thread. This expansion is taken up by the spring and the silk thread, which causes the pulley to rotate and the pointer is deflected.

3.7.3 Deflecting Torque

The deflection of the pointer of the hot-wire instrument is proportional to the extension of the hot wire, which is itself proportional to the square of the current. Hence,

Deflecting torque, $T_d \propto I^2$

If spring control is used, then

Controlling torque, $T_c \propto \theta$ (deflection)

But, for balance $T_d = T_c$

$\theta \propto I^2$

Thus, these instruments have a square-law type scale. They read the r.m.s value of current and are independent of its frequency.

3.7.4 Damping

Damping is provided by a thin aluminium disc fixed to the spindle and moving between the poles of a permanent magnet, as shown in Fig. 3.14. If there is any tendency to oscillate, eddy currents are set up in the disc and the direction of these current is such as to oppose the motion producing them. Adjustment is provided for the zero position of the pointer by a spring moved by means of a screw at one end of the hot wire.

These instruments are primarily meant for use as ammeters, but can be used as voltmeters by connecting a high resistance in series with the instrument. These instruments are suited both for a.c. and d.c. work.

3.7.5 Advantages

Following are the advantages of hot-wire instruments:

(i) Since the deflection of the pointer depends on the r.m.s value of the alternating current, it can be used both for a.c. and d.c.
(ii) These instruments are free from wave-forms and frequency errors.
(iii) As the instruments do not depend upon any magnetic effect for their operation, they are free from external stray magnetic field errors.

3.7.6 Disadvantages

Following are the disadvantages of hot-wire instruments:

(i) Very slow response of the circuits, as the wires take time to heat up.
(ii) High power consumption as compared to moving coil instruments.
(iii) Their zero position needs frequent adjustments due to changes in room temperature.
(iv) Inability to withstand overload because the hot wire is so fine that it may melt before the fuse.
(v) Inability to withstand mechanical shocks because the wire is very fragile.

Hot-wire instruments are now obsolete and have been replaced by the more sensitive, more accurate and better-compensated combination of thermoelectric heating element and PMMC movement.

3.8 INDUCTION INSTRUMENTS

Induction type instruments are suitable for a.c. circuits only, as their working depends on induced current due to an alternating flux.

3.8.1 Operating Principle

All induction-principle type instruments depend for their action upon the torque produced by the reaction between a flux, whose magnitude depends upon the value of current or voltage to be measured, and eddy currents which are induced in a metal disc or drum by another flux, whose value again is dependent upon the current or voltage to be measured.

Since the magnitude of the eddy current is proportional to that of the flux inducing it, the torque at any instant is proportional to the square of the current or voltage to be measured, and the mean torque is proportional to the mean square value of this current or voltage.

Therefore, $T_m \propto \phi_m \propto I \cos \theta$ (3.17)

where T_m is the mean torque
ϕ_m is the r.m.s value of flux
I is the r.m.s. value of current
θ is the phase displacement

There are two general types of induction instruments:

(i) the Ferraris type

(ii) the shaded-pole type

3.8.2 Ferraris-Type Induction Instrument

This type of instrument employs splitting of the winding of the electromagnet, in which the flux exists, into two portions; one of which is highly inductive while the other is non-inductive.

Construction It consists of a drum and a moving system which are carried by a spindle whose ends fit in jewelled cups or bearings. There is a cylindrical laminated iron core inside the drum to strengthen the magnetic field cutting the drum. This spindle also carries an aluminium damping disc, the edge of which moves in the air-gaps of two permanent magnets to provide damping torques. Figure 3.15 shows a diagram of the Ferraris-type induction instrument.

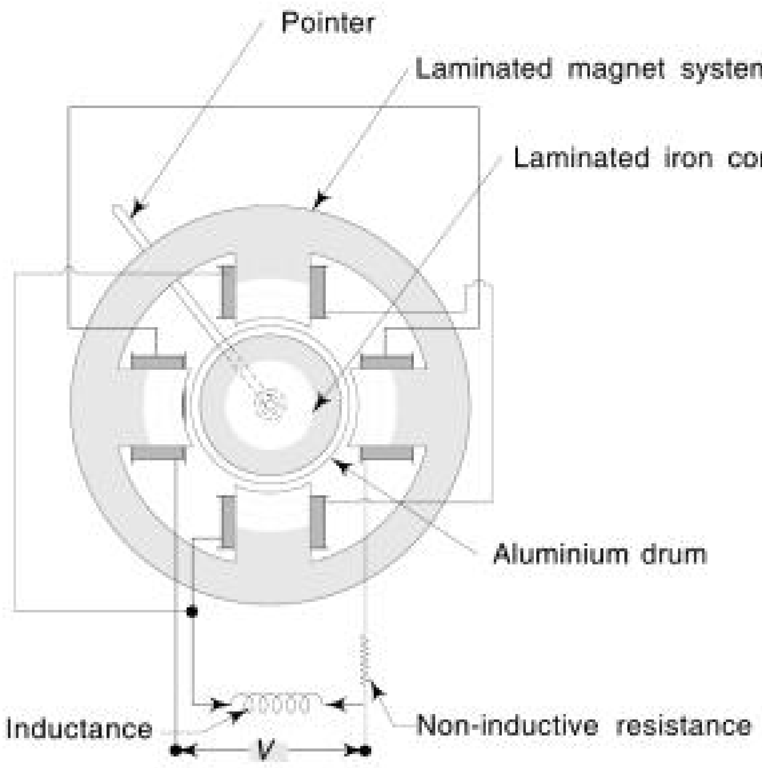


Fig. 3.15 *Ferraris-type Induction Instrument*

A control spring is provided to prevent the continuous rotation of the drum. The drum will rotate only through some angle less than 360°.

Working Principle This type of instrument operates on the same principle as the induction motor. A rotating field is produced by two pairs of coils wound upon a laminated magnet system, as shown in Fig. 3.15. These pairs of coils are both supplied from the same source, but a phase displacement of approximately 90° is produced in the currents flowing in them by connecting an inductance in series with one pair and a high resistance with the other, to produce a rotating magnetic field. This rotating field induces currents in an aluminium drum and causes this drum to follow its rotation. If the drum is free to rotate, it will rotate at a speed slightly less than that of the rotating field but in the same direction of the field.

Deflecting Torque The mean deflecting torque of the Ferraris-type induction instrument is given by

$$T_m \propto \frac{I^2 f}{Z} \tag{3.18}$$

Also

$$T_m \propto \frac{V^2 f}{Z} \tag{3.19}$$

Where,
I = r.m.s. value of current
V = r.m.s. value of voltage
f = frequency of the supply
Z = impedance

3.8.3 Shaded-Pole Type Induction Instrument

This type of instrument employs splitting of the phase of the working flux by a copper band placed round a portion of the poles of the electromagnet.

Construction It consists of a thin aluminium disc mounted on a spindle which is supported by jewelled bearings. The spindle carries a pointer and a control spring is attached to it. The edge of the disc moves in the air-gap of a laminated electromagnet which is energized either by the current to be measured or by a current proportional to the voltage to be measured. Figure 3.16 shows a diagram of the shaded-pole type induction instrument.

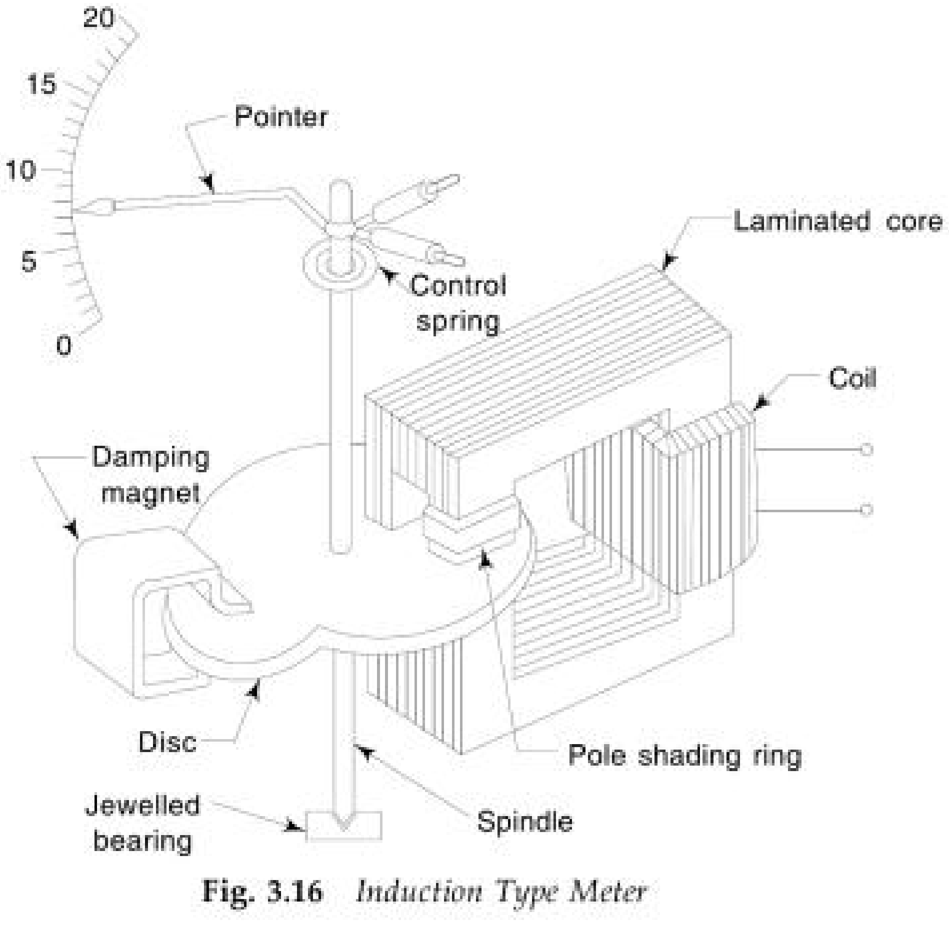


Fig. 3.16 *Induction Type Meter*

Damping torque is produced by a permanent magnet which is placed at the opposite side of the disc from the electromagnet, so that the disc serves for damping as well as operating purposes.

As no torque is produced by a flux from a single-phase current, a phase-shifting arrangement is provided by shading a part of the pole core, as shown in Fig. 3.16. About one-third of the pole is encircled by a copper strip.

Operating Principle When alternating current is supplied to the electromagnet, eddy currents are induced in the shading ring, and the flux inside the shaded portion of the core lags behind the main flux by an angle of 40° to 50°. This phase displacement produces a torque on the disc which is proportional to the square of the current or the voltage to be measured.

Therefore, deflecting torque $T_d \propto I^2$

and controlling torque $T_c \propto \theta$ (for spring control)

where θ is the deflection.

For steady deflection $T_c = T_d$

Therefore, $\theta \propto I^2$

3.8.4 Advantages of Induction Instruments

The following are the advantages of induction instruments:

(i) A full-scale deflection of about 300° obtainable, giving a long and open scale.
(ii) Stray magnetic fields having limited effect upon their readings.
(iii) Good and very efficient damping.

3.8.5 Disadvantages of Induction Instruments

The following are the disadvantages of induction instruments:

(i) Their power consumption being fairly high, they are more expansible.
(ii) They can be used for a.c. measurement only.
(iii) The scale is cramped initially, because the deflecting torque is proportional to the square of the current or voltage to be measured.

In order to improve the scale of the instrument, the disc is sometimes made cam-shaped instead of being circular.

3.8.6 Errors in Induction Instruments

Following are the errors in induction instruments:

(a) Error Due to Frequency Variation Variation of frequency directly affects the deflecting torque for a given current because the deflecting torque is directly proportional to the frequency. The value of impedance Z also varies with the change in frequency.

Some compensation for frequency error can be provided by shunting the induction ammeter by non-inductive shunt.

(b) Error Due to Temperature Variation Since the resistance of the eddy current paths in the disc are dependent upon the temperature, it may produce serious errors.

Compensation for temperature error is obtained by shunting the instrument (in case of an ammeter) with a shunt of material having a higher temperature coefficient than that of aluminium of which the disc is made.

In voltmeters, a combination of shunt and swamping resistance is often used in series with the instrument.

3.8.7 Applications of Induction Instruments

Induction instruments are used for the following purposes:

(i) as an ammeter
(ii) as a voltmeter
(iii) as a wattmeter

3.9 ELECTROSTATIC INSTRUMENTS

These are the only instruments that are directly voltage sensitive and do not depend on a current for their operation. Although electrostatic instruments are used for other measurements also, voltmeters are the most commonly used form.

3.9.1 Operating Principle

The operating principle of an electrostatic instrument depends on the force of attraction between two or more electrically charged conductors between which a potential difference is maintained, and this force gives rise to a deflecting torque. The electrostatic mechanism resembles a variable capacitor, where the force existing between the two parallel plates is a function of the potential difference applied to them.

Basically, there are two types of electrostatic (also known as electrometers) instruments:

(i) Quadrant type
(ii) Attracted-disc type

3.9.2 Quadrant-Type Electrostatic Voltmeter

Quadrant-type electrometers are used for the measurement of voltage upto 10 to 20 kV. Figure 3.17 illustrates the principle of this instrument.

Construction and Working It consists, essentially, of two sets of metal plates, one movable and the other fixed, the former being of very light construction (e.g. of aluminium). The movable plate, together with the end of the spiral spring, is attached to the spindle carrying the pointer of the instrument (Fig. 3.17). These two plates (fixed and movable) constitute a capacitor whose capacitance changes as the pointer moves on the scale.

When the voltage to be measured is applied between the fixed and movable plates, the plates acquire opposite charges that are proportional to the potential difference or the voltage. The electric field set up between the plates causes the movable plate and pointer to move to the right until the deflecting force is balanced by a spring or other restoring force. The deflecting torque is directly proportional to the square of the applied voltage and, thus, these instruments measure r.m.s. voltages.

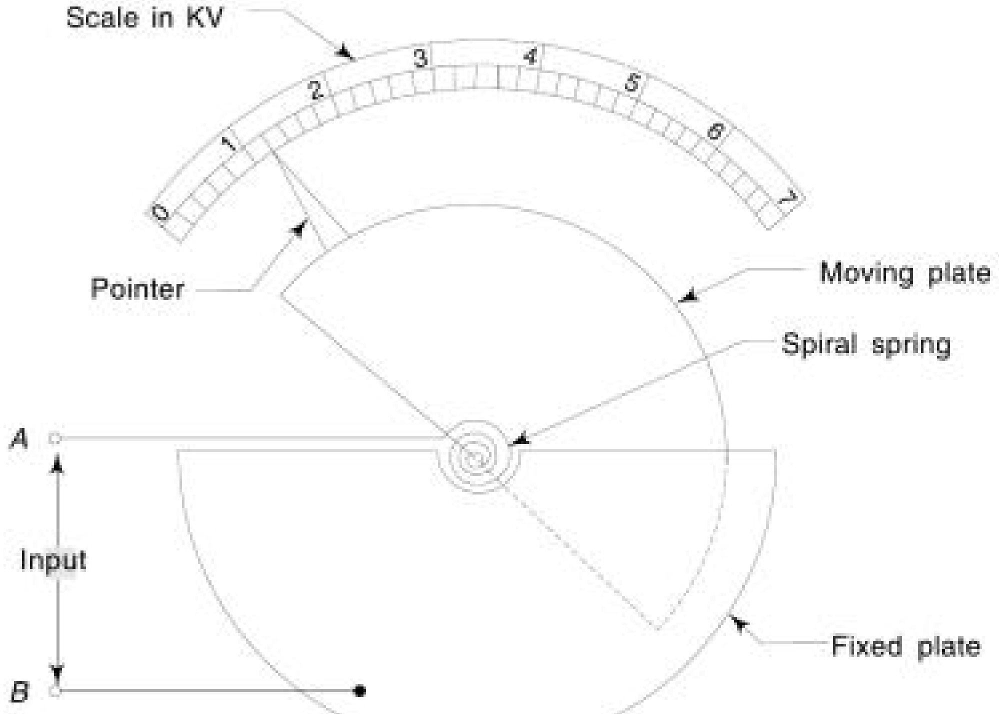


Fig. 3.17 *Quadrant-type Electrostatic Voltmeter*

The deflecting torque of this type of instrument is very small, unless the applied voltage is extremely large. The force on the plates may be increased by using a greater number of quadrants. Such an instrument, known as "Kelvin's multicellular electrostatic voltmeter", is shown in Fig. 3.18.

Kelvin's Multicellular Electrostatic Voltmeter Such voltmeters can be used to measure voltages as low as 30V. This reduction in the minimum limit of voltage is obtained due to the increase in the number of quadrants, which

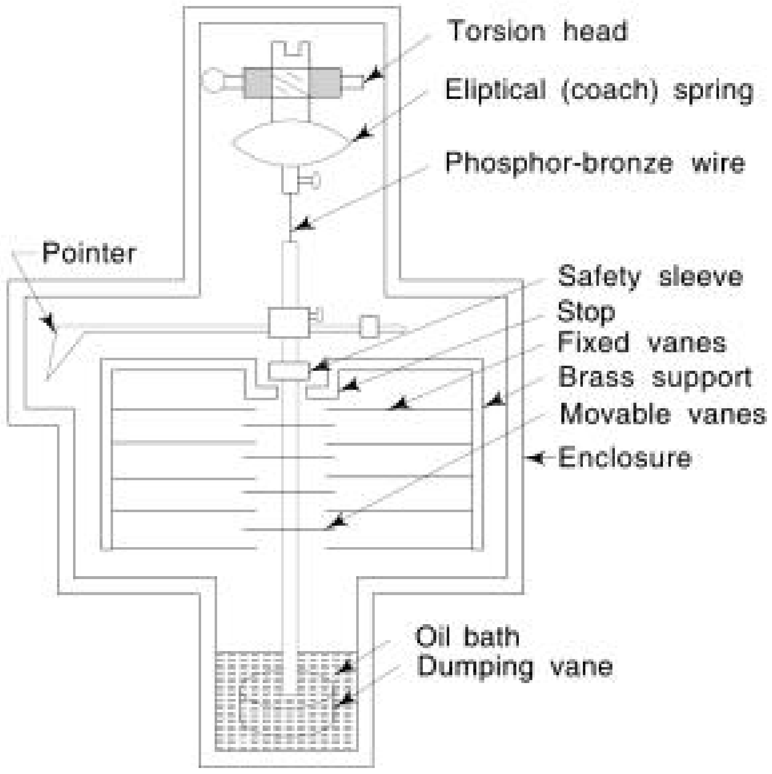


Fig. 3.18 *Kelvin's Multicellular Electrostatic Voltmeter*

increases the operating force. Figure 3.18 is a diagram of a Kelvin multicellular electrostatic voltmeter.

In this type of instrument, the fixed system consists of a cellular structure composed of two sets of triangular metal plates which are fixed to brass supports. The moving system consists of an equal number of aluminium vanes mounted on a spindle and suspended by a phosphor-bronze wire. The upper end of the wire is connected to an elliptical spring (also known as coach spring) which is mounted on a torsion head for zero adjustment. The spring is provided for protection against accidental fracture of suspension due to vibration and other such factors. A safety sleeve is placed to come in contact with a stop in the event of any sudden jerk which would otherwise tend to break the suspension. A pointer attached to the moving system deflects on the scale.

The controlling torque is provided by the tension in the phosphor-bronze wire when the vanes are deflected from the zero position.

The damping is provided by a vane immersed in an oil dashpot.

3.9.3 Attracted-Disc Type Electrostatic Voltmeter

In the attracted-disc electrometer, the force of attraction between the charged plates is used as a measure of the potential difference (or voltage). This type of voltmeter is used for the measurement of voltages upto 500 kV.

Construction and Working Figure 3.19 shows a diagram of the attracted- disc type electrostatic voltmeter (or electrometer). It consists of two discs, one fixed and the other moving, mounted parallel to each other. The fixed disc is earthed while the movable disc is suspended by a spring (known as coach spring) from a micrometer head, for adjustment. A guard ring is placed surrounding the movable disc, separated by a small air-gap. The guard ring is electrically connected to the moving disc and helps to make the field between the moving and fixed discs uniform. The effective area of the moving disc becomes equal to its actual area plus half the area of the air-gap. A fine cross-hair is carried by the moving disc so

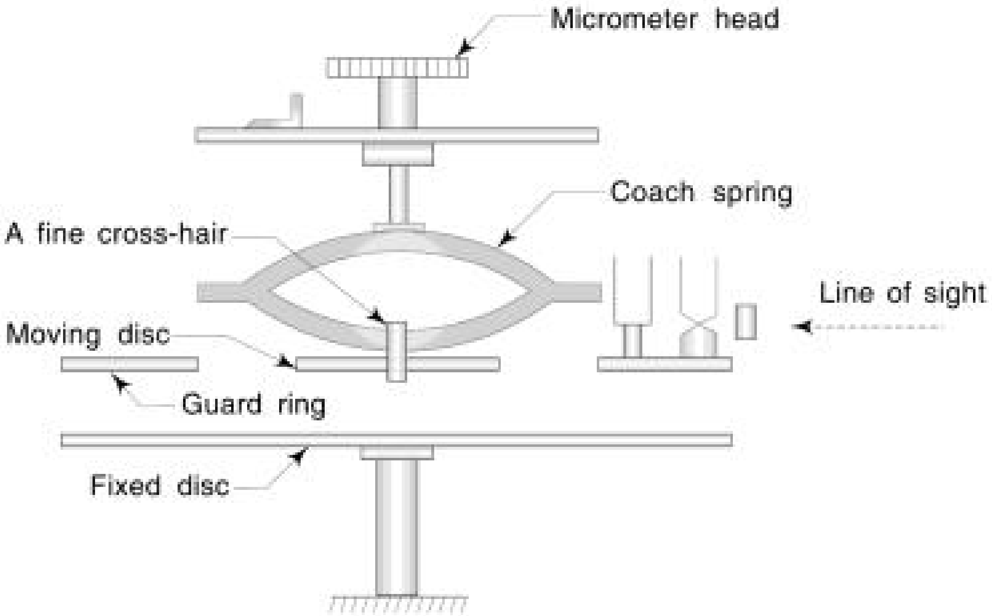


Fig. 3.19 *Attracted-Disc Type Electrostatic Voltmeter*

that, by means of a sighting device consisting of lenses and two finely pointed rods, the zero setting of the disc may be accurately determined. The movable plate is connected to the positive end of supply.

When the potential difference (or voltage) to be measured is applied between the two discs, the moving disc is attracted towards the fixed disc, and is brought back to its zero position by turning the micrometer head. The movement of this head, required to return the disc to zero, indicates the force with which the moving disc is pulled downwards.

The instrument can be calibrated by first short-circuiting the instrument, then setting the moving disc to its zero position, adding a known weight to the moving disc and observing the movement of micrometer head necessary to bring the moving disc back to its original position. The movement of the moving disc is balanced by a control device which actuates a pointer attached to it that moves over a calibrated scale.

3.9.4 Advantages of Electrostatic Instruments

The following are the advantages of electrostatic instruments:

(i) They can be manufactured with a very high accuracy.

(ii) They can be used on either a.c. or d.c. and over a fairly large range of frequencies.

(iii) The instruments may be calibrated with d.c., and yet the calibration would be valid for a.c. also since the deflection is independent of the waveform of the applied voltage.

(iv) Since no iron is used for their construction, they are free from hysteresis, eddy current losses and temperature errors.

(v) Their power loss is negligible.

(vi) They are unaffected by stray magnetic field although they have to be guarded against any stray electrostatic field.

(vii) Once the discs are charged, no more current is drawn from the circuit and the instrument represents infinite impedance.

(viii) They can be used upto 1000 kHZ frequency without any serious loss of accuracy.

(ix) They do not draw any continuous current on d.c. circuits and that drawn on a.c. circuits is extremely small. Hence, such voltmeters do not cause any disturbance to the circuit to which they are connected.

3.9.5 Limitations or Electrostatic Instruments

The following are the limitations of electrostatic instruments:

(i) Their use is limited to certain special applications, particularly in a.c. circuits of relatively high voltage where the current taken by other instruments would result in erroneous indications.

(ii) Low voltage voltmeters are liable to friction errors.

(iii) Since the deflecting torque is proportional to the square of the voltage, their scales are not uniform although some uniformity can be obtained by suitably shaping the quadrants of the instruments.

(iv) They are expensive and are not likely to be durable.

(v) They are, inherently, laboratory-type rather than industrial-type instruments.

3.10 INSULATION TESTING MEGGER

Insulation testing megger is a portable instrument used for testing the insulation resistance of a circuit, and for measuring the resistance of the order of megaohms in which the measured value of resistance is directly indicated on a scale. The indication of the megger is independent of the voltage.

3.10.1 Construction

It consists of two primary elements, a d.c. generator of the magneto-type, usually hand-driven, which supplies the current for making the measurement, and the instrument movement which indicates the value of resistance under measurement. *A* diagram of the megger is shown in Fig. 3.20. The instrument consists of two coils *A* and *B*, both mounted on the same moving system and moving between two poles faces of a permanent magnet. The flux is supplied by the permanent

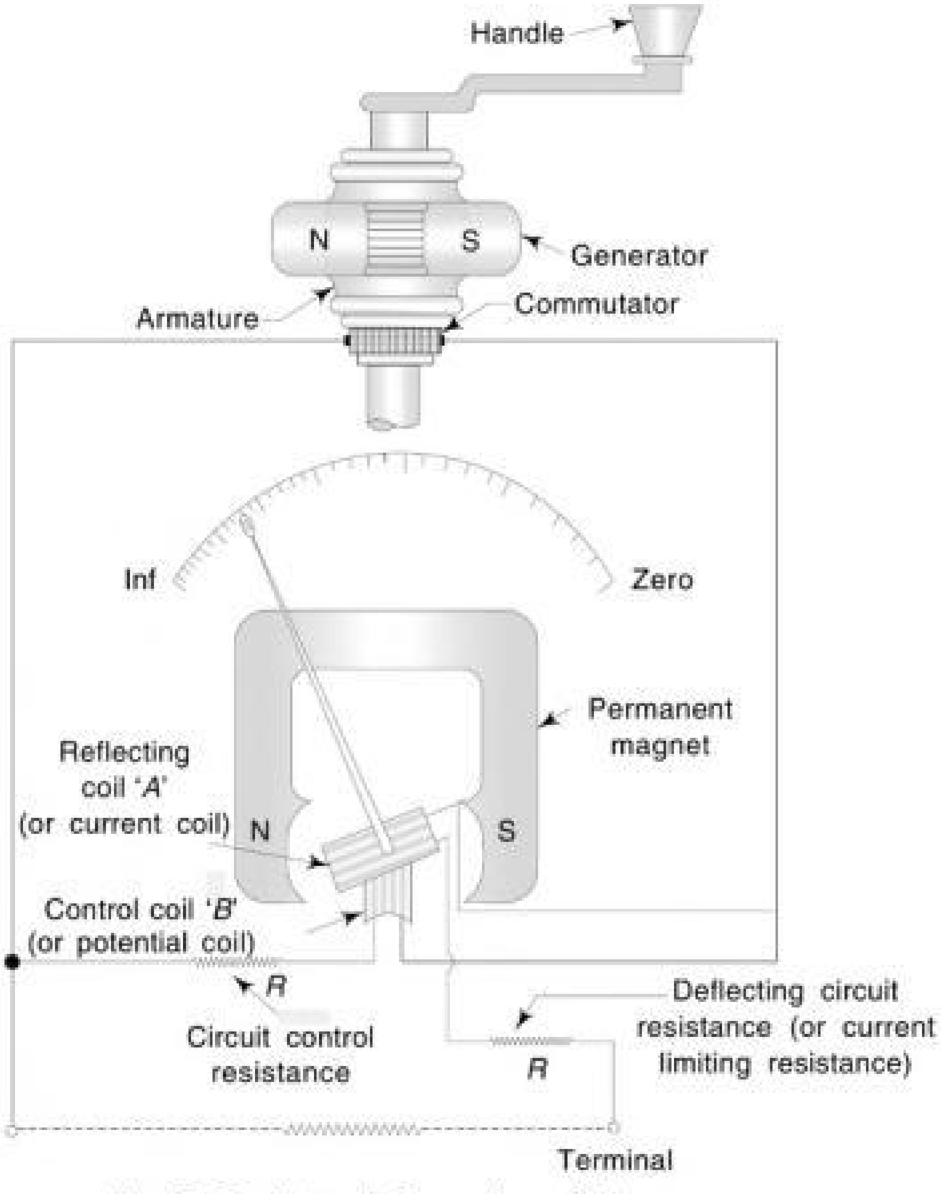


Fig. 3.20 *Internal Connection of Megger*

magnet through the pole pieces and core, which increases the permeance of the magnetic circuit and produces a radial field. Coil *A*, which is known as the current (or reflecting) coil, is connected to the negative brush of the generator and line terminal, in series with a current-limiting resistance. Coil *B*, which is known as the potential (or control) coil, is connected across the armature brushes in series with a suitable resistance *R*. The moving system is mounted in spring-supported jewel bearings and is free to rotate on its axis. Current is led to the coils by flexible conducting ligaments which have negligible tension. Hence, when the generator is not being operated, the pointer floats over the scale. Under these conditions, it may remain in any position whatsoever.

The voltage for testing is supplied by a small hand generator incorporated in the instrument, and is usually of 250 or 500 V in smaller sizes and 1000 V in larger sizes. Its speed is stepped up through gears. In order that the measuring voltage remains at its nominal constant value, a slip clutch is provided which operates when the armature reaches its normal speed.

3.10.2 Working Principle

When the terminals of the megger are open-circuited, or if a resistor of infinite resistance is connected across the terminals and the crank (or handle) is being operated, the generated voltage so produced is applied across the coil *B* and current flows through it, but no current flows through the current coil *A*. Therefore, the torque is produced due to the potential coil *B* only, which rotates the pointer until the scale points to infinity. It indicates that the resistance of the external circuit is too large for the instrument to measure.

When the testing terminals of the megger are closed through a low resistance or are short-circuited, a large current (limited by *R*) passes through the current coil *A*. The deflecting torque is produced by the current coil which overcomes the small torque of potenital coil *B* and rotates the pointer until the scale points to zero, thus showing that the external resistance is too small for the instruments to measure.

Hence, the scale may be calibrated in terms of resistance in order to measure any value between zero and infinity.

3.10.3 Applications of Megger

Meggers are used in industries for observing the following tests:—

(i) open-circuit tests
(ii) short-circuit tests
(iii) continuity tests
(iv) ground tests
(v) earth resistance tests

An orientation table for ammeters, voltmeters and wattmeters is given in Table 3.1.

3.11 INSTRUMENT TRANSFORMER

Instrument transformers are general devices used for extending the range of a.c. measuring instruments for the measurement of electric current and voltage.

Table 3.1 *Orientation Table for Ammeters, Voltmeters, and Wattmeters*

	FEATURES				
Meters	*Type of meter movement*	*Accessories required*	*Full-scale meter range*	*Possible overload in multiples of full-scale for noted time*	*Recommended applications*
Ammeters (a.c.)	Moving-iron	None	1–50 A	*For meters* 1.2 × : 8 h 100 × : 1 s	General use upto 750 volts
	Moving-iron	Transformer	10–8000 A	*For Transformer* 50 × 2 : s	High range over 750 volts, long meter leads
Ammeters (d.c.)	Permanent magnet moving-coil	None	0.02×10^{-3}–50 A	1.2 × : 8 h	General use
	Permanent magnet moving-coil	Shunt	20–20,000 A	100 × : 1 s	High range
Voltmeters (a.c.)	Moving-iron	None	3–600 V	*For meters* 1.2 × : continuous 100 × : 1 s	General use
	Moving-iron	Transformer	150–18,000 V	*For Transformer* 1.2 × : continuous 1.25 × : 1 min	High range, circuit isolation
Voltmeters (d.c.)	Permanent magnet moving-coil	None	1–600 V	1.2 × : continuous 100 × : 1 s	General use
	Permanent magnet moving-coil	Resistor	250–30,000 V	1.2 × : continuous 100 × : 1 min	High range, High sensitivity
Wattmeters Single-phase (a.c.)	Electrodynamic	None	125–1000 W	*For current* 1.5 × : continuous 10 × : 1 min	Low power, single-phase, 2-wire circuits
	Electrodynamic	Transformer	$100–100 \times 10^6$ W	*For voltage* 1 × 2 : continuous 10 × : 1 min	General use, single-phase circuits
Wattmeters three-phase (a.c.)	Electrodynamic	Transformer	$1000–100 \times 10^6$ W	–do–	General use, three-phase three-wire.
Wattmeters (d.c.)	Electrodynamic	None	100–1000 W		General use, average-power

They are used to measure a.c. current and voltage at generating stations, transformer stations and at transmission lines, in conjunction with ac measuring instruments (such as ammeters, voltmeters, wattmeters, etc.).

3.11.1 Classification

According to the use, instrument transformers are classified in the following two types:

(i) Current (or Series) Transformer (CT) *Current transformers* are used to extend the range of ammeters, and the current coils of wattmeters and energymeters,

(ii) Potential (or Voltage) Transformer (PT) *Potential transformers* are used to extend the range of voltmeters, and the pressure coils of wattmeters and energymeters.

In using instrument transformers for current and voltage measurements, the ratio of the magnitudes of the primary quantities to the corresponding secondary must be known. For satisfactory and accurate performance, it is necessary that the ratio of transformation of the instrument transformer should be constant within close limits. However, in practice, neither transformation ratio $\frac{I_1}{I_2}$ in case of C.T. nor voltage transformation ratio $\frac{V_1}{V_2}$ in case of P.T., remains constant. Instead the transformation ratio is found to be dependent on the exciting current and the current and power factor of the secondary circuit. This causes an error known as *ratio error* of the transformer that depends on the working component of primary circuit. On the other hand, the phase angle between the primary and secondary current is not exactly 180° but slightly less introducing another error known as *phase angle error*. The process of finding out these errors is termed as testing of instrument transformers. At very low power factor, the phase angle may be negative.

Figure 3.21 shows the diagram for the use of instrument transformers in a typical measurement application. It illustrates the connection of instrument transformers in a three-wire three-phase circuit, including two ammeters, two voltmeters and two wattmeters. The C.T.s are connected in phase lines P and R, whereas P.T.s are connected across phase lines P and Q and phase lines R and Q. The secondary windings of the C.T.s feed the ammeters and the current coils of the wattmeter, whereas that of the P.T.s are connected to the voltmeter coils and the potential coils of the wattmeter.

As shown in Fig. 3.21, the current transformer is used with its primary winding connected in series with the line whose current is to be measured. Hence, the primary current is not determined by the load on the secondary of the current transformer. The primary of the current transformer consists of very few turns and, hence there is no appreciable voltage across it. While its secondary winding has large number of turns determined by the turn ratio. The wattmeter or ammeter current coil is connected directly across the secondary terminals. Thus, a current transformer operates its secondary nearly under short circuit conditions. The secondary circuit is connected to the ground.

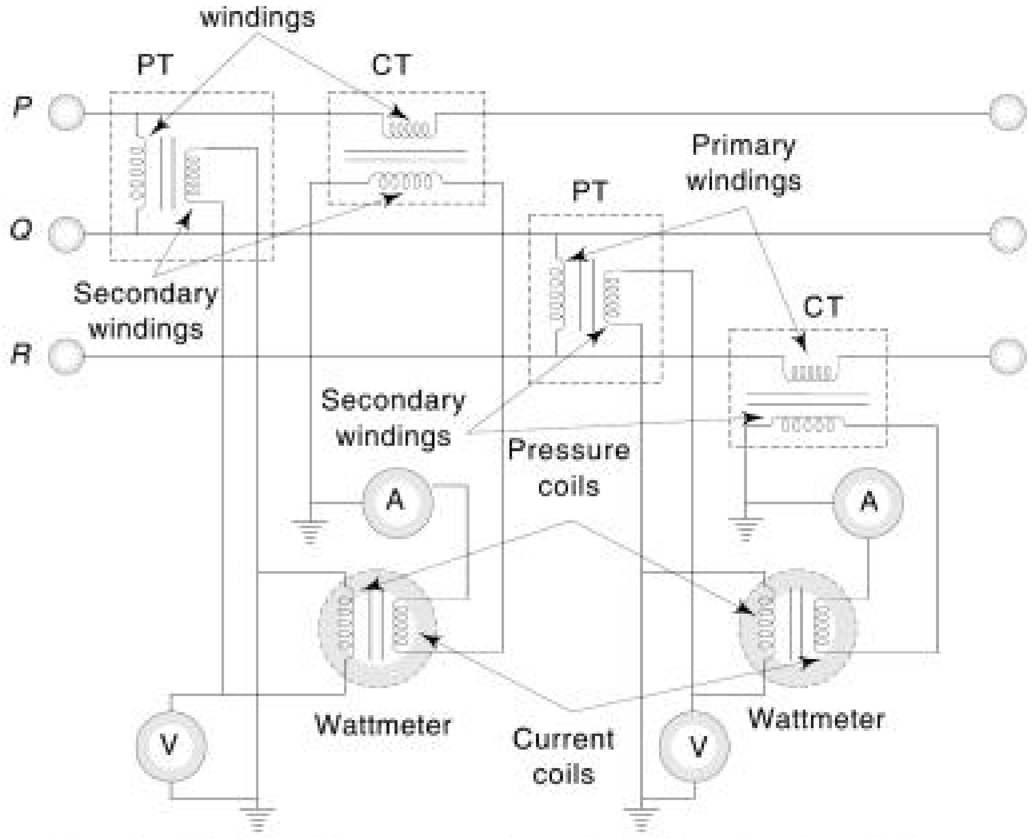


Fig. 3.21 *Application of Instrument Transformer in Three-phase Measurement*

The potential transformer is used to operate the potential coils of wattmeter, voltmeters and relays from high voltage lines. Its primary winding is connected across the lines as shown in Fig. 3.21. The voltmeter for the measurement of line voltage is connected across the secondary winding. For safety reasons the secondary winding is completely insulated from high-voltage primary and is, in addition, grounded for providing protection to the operator.

3.11.2 Advantages of Instrument Transformers

(i) A single range instrument can be used for measurement of currents or voltages of various ranges simply by using a multi-range current or voltage transformer or several single-range transformers.

(ii) When the measurement is to be done on a high-tension circuit (transmission line), the instrument can be located at some distance from the circuit, thus giving great safety to the control room operator.

(iii) As the measuring instrument is isolated from high-tension circuit, it need not be insulated for high voltage.

(iv) With the help of a current transformer with suitably split and hinged core, the current in a heavy current bus-bar can be measured without breaking the current circuit. The split core of the current transformer simply clamps round the current carrying bus-bar. Thus, the bus-bar acts as the primary winding of the transformer.

(v) When a.c. indicating instruments are used in conjunction with instrument transformer, their readings do not depend upon their constants viz. *R*, *L*, and *C* as is the case with shunts and multipliers.

(vi) It is very cheap and moderate rating instrument that can be used to measure large currents and high voltages.

(vii) There is low power consumption in metering circuit.

(viii) With the standardization of C.T. and P.T. secondary winding ratings, it is possible to standardize instruments around these ratings and, therefore, there is great reduction in the costs of instrument transformers and instruments.

(ix) Replacement of instrument is easy on account of the standardization of the ratings.

(x) Several instruments can be operated from a single instrument transformer.

3.11.3 Applications of Instrument Transformers

(i) Extend the range of the a.c. measuring instrument (similar to that of the multiplier used to extend the range of a d.c. meter).

(ii) Isolate the measuring instrument from the high-voltage power line.

(iii) Widely used for very precise measurements as well as routine measurement.

3.12 POTENTIOMETER

Potentiometer is an instrument for measurement of an unknown electromotive force (e.m.f.) or potential difference (voltage) produced by the flow of a known current in a network of circuits of known characteristics. It is an instrument by which an unknown voltage is measured by comparing it with a known voltage. The known voltage may be supplied by a standard cell or any other known voltage-reference source.

Potentiometers are used extensively in measurements where

(i) precision required is very high as compared to that can be obtained by deflection instruments

(ii) it is important that no current be drawn from the source under measurements

(iii) the current must be limited to a small value.

3.12.1 Advantages of Potentiometers

(i) It has very high accuracy because the result obtained does not depend upon the actual deflection of a pointer, as is the case in deflection instruments. Its result depends upon the accuracy with which the voltage of the reference source is known.

(ii) It has no power consumption from the circuit containing unknown e.m.f., when it is balanced (because no current flows).

(iii) The determination of voltage by potentiometer is quite independent of the source resistance.

3.12.2 Application of Potentiometers

(i) Measurement of voltage.

(ii) Measurement of current.

(iii) Measurement of resistance.

(iv) Measurement of Power.

(v) Calibration of ammeters, voltmeters and wattmeters.

There are two types of potentiometers used in industry:

(a) D.C. Potentiometers

(b) A.C. Potentiometers

3.12.3 D.C. Potentiometers

There are various types of d.c. potentiometers that are used. Some of the d.c. potentiometers used in industry are described below.

Slide-wire Potentiometer

Construction Slide-wire type is the simplest and basic form of d.c. potentiometer. It consists of a slide wire AB of uniform section and higher resistance, as shown in Fig. 3.22. An adjustable and steady current I, regulated by resistance R, is maintained by a constant source of e.m.f. (battery) E_1. A galvanometer G is connected in series with E_1 along with switch S. An e.m.f. source E_2 whose voltage is to be measured, is connected in parallel with the slide-wire.

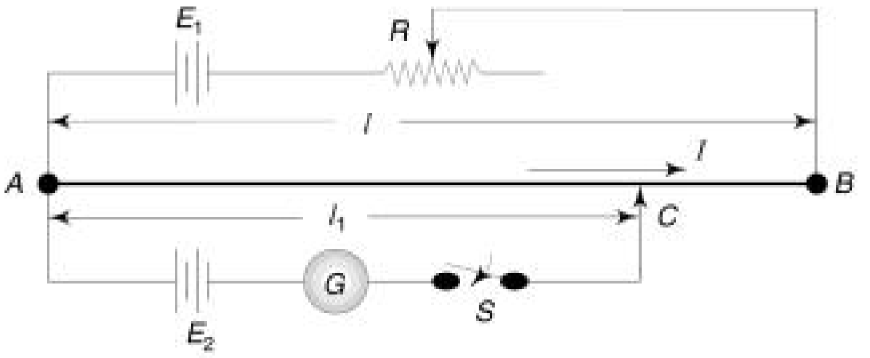


Fig. 3.22 *A Slide-Wire Potentiometer*

Working Let l be the length of the potentiometer slide-wire AB, r be its resistance per unit length and I be the current flowing through the slide-wire AB when switch S is open. Then the potential difference (voltage) V_{AB} across the slide-wire AB will be given as

$$V_{AB} = I\rho\, l$$

When switch S is closed and the potential difference (voltage) V_{AC} across the slide-wire AC is greater than the e.m.f. of E_2, a current will flow through the galvanometer in the direction A to C. It may be mentioned here that the E_2 is connected so as to oppose this current. If these e.m.f's are equal, no current will flow through the galvanometer. If length of the slide-wire AC is l_1, then the potential difference (voltage) V_{AC} across the slide-wire AC will be given as

$$V_{AC} = I\rho\, l_1$$

Hence

$$\frac{V_{AB}}{V_{AC}} = \frac{l}{l_1} \tag{3.20}$$

If one of the batteries is a standard cell of known voltage V_{AC}, then the e.m.f. of the battery E_2 is given by

$$V_{AB} = \frac{l}{l_1} \times V_{AC} \tag{3.21}$$

The accuracy of measurement depends to large extent upon the accuracy with which $\frac{l}{l_1}$ can be determined. Thus, the longer the slide-wire the less is the percentage error. For precise measurements, the effect of a very long slide-wire is achieved by connecting a number of resistance coils in series with a comparatively short slide.

Standardization The process of adjusting the working current so as to match the voltage drop across a portion of the sliding wire against a standard reference source, is known as *standardization* of potentiometer. Standardization makes the above slide-wire potentiometer directly readable, i.e. the e.m.f. or voltage of the battery may be measured without any computation.

To standardize or make the simple slide-wire potentiometer directly readable, the battery E_2 of galvanometer circuit in Fig. 3.22 is replaced by a standard cell E_S, usually, Weston cell having e.m.f. of 1.0183 V, by means of double throw switch S_D, as shown in Fig. 3.23. The slide-wire contact C is now set at a length to read 1.0183 cm mark on the linear scale mounted beside the slide-wire. The current I in the slide-wire is adjusted by means of variable resistance R until the galvanometer gives zero deflection. Now, without changing the slide-wire current R, the standard cell E_S is replaced by a cell E_2 of known e.m.f. by means of the switch S_D and the potentiometer is balanced by adjusting the position of the slide contact C. The e.m.f. of E_2 may be read directly from the scale under balanced condition. If l_1 is this length then from Eq. 3.29

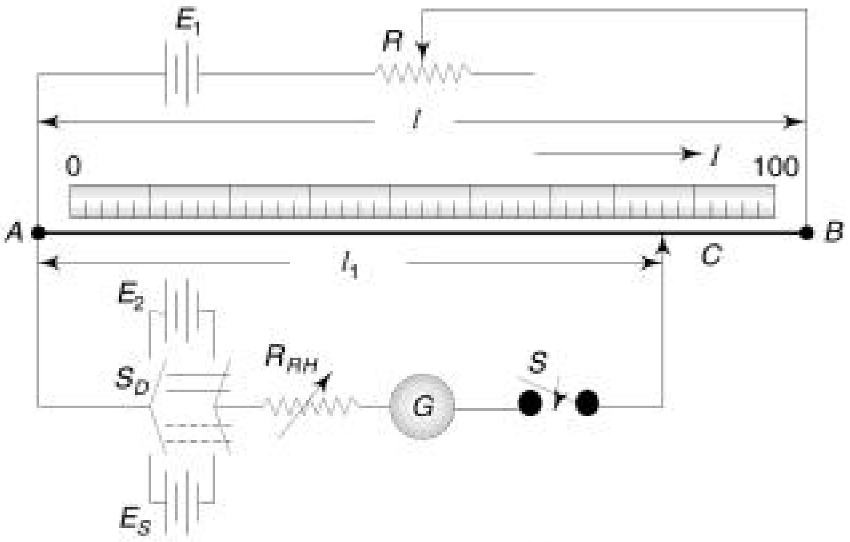


Fig. 3.23 *Standardization of Potentiometer*

$$\frac{V_S}{V_{AC}} = \frac{1.0183}{l_1}$$

But V_{AC} = e.m.f. of the Weston cell = 1.0183 V

Hence,
$$V_{AC} = I_1 \frac{1.0183}{10.183} = I_1 \qquad (3.22)$$

Thus, the voltage at any point along the slide-wire is proportional to the length of the slide-wire and the reading on the scale gives the magnitude of the cell's e.m.f.

Crompton Potentiometer The slide-wire potentiometer discussed earlier is of very limited use since its accuracy depends on uniformity of the wire (longer the slide-wire the less is the percentage error). Crompton potentiometer is the modified version of the slide-wire potentiometer wherein calibrated dial resistors with a small circular wire of one or more turns are used thereby reducing the size of the instrument. The effect of a very long slide-wire is achieved by connecting a number of resistance coils in series with a comparatively short slide-wire.

Construction Circuit diagram of a Crompton d.c. potentiometer is shown in Fig. 3.24. It consists of a graduated slide-wire *AB*, having resistance usually of the order of 10 ohms. The slide-wire is connected in series with 14 (or more) resistance coils *PA*, each of which has a resistance exactly equal to that of the slide-wire. There are two slide (moving) contacts C_1 and C_2; C_1 sliding over the slide-wire *AB* and C_2 sliding over the studs of the resistance coils *PA*. Two variable resistors, R_1 consisting of a number of coils for coarse adjustment and R_2 in the form of a slide-wire fine adjustment of the potentiometer current, are used in series with a battery E_1 of 2 volts.

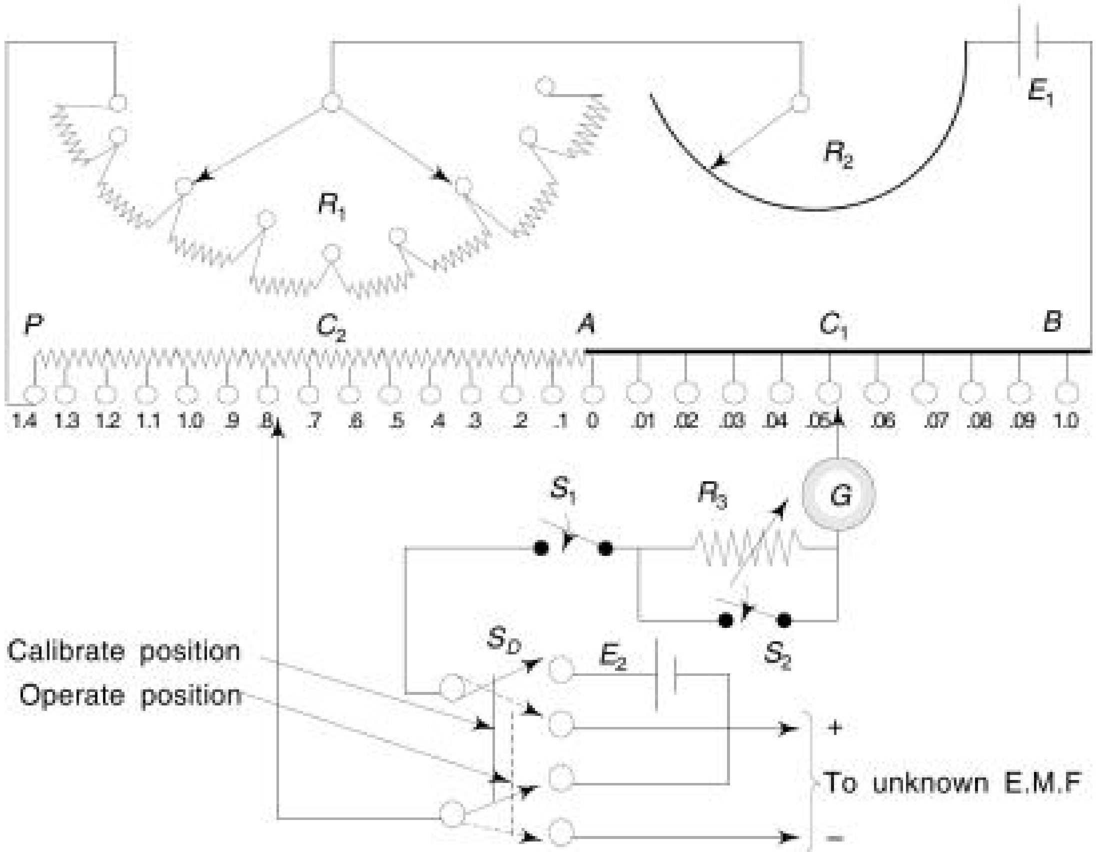


Fig. 3.24 *Crompton Potentiometer*

A galvanometer G is connected in series with a switch S_1 and a double throw switch S_D, by means of which either the standard cell (battery) E_2 or the e.m.f. to be measured, can be connected in the galvanometer circuit. In one position, the switch S_D connects the galvanometer with standard cell (battery) E_2 and this position is usually referred as *calibrate position*. In other position, the switch S_D connects the galvanometer to the unknown e.m.f. and this position is usually referred as *operate position*. Proper polarity must be observed while making connections with the batteries to avoid damage to the potentiometer.

Working First of all, before use, the galvanometer is heavily shunted and then the potentiometer is standardized (to give direct reading) by putting the double throw switch S_D in calibrate position. For this, if Weston type standard cell of e.m.f. of 1.0183 volts is used, the slide contact C_2 is set on stud 1.0 and C_1 at 0.0183 on the slide-wire. The resistors R_1 and R_2 are then adjusted to obtain no deflection of the galvanometer at its full sensitivity, i.e. when S_2 is closed. This setting of R_1 and R_2 is kept fixed for all further measurements.

Now, the double throw switch S_D to which the battery of unknown e.m.f. has been connected, is put in operate position. Again contacts C_1 and C_2 are adjusted to obtain the balance of the potentiometer, i.e., no deflection is observed in the galvanometer. The reading of the potentiometer will then directly give the e.m.f. to be measured.

Disadvantages of Crompton Potentiometer Following are the main disadvantages

(i) It is not possible to arrange for the contacts C_1 and C_2 to coincide and thus true reading cannot be obtained.

(ii) In order to obtain steadiness of the current, the current has to be allowed to flow through the potentiometer wire for a few minutes before making a measurement. If balancing takes longer time then the standardization should be checked.

(iii) It is necessary to change the dial and slide-wire settings of the potentiometer, each time when the potentiometer is standardized or the standardization is checked.

(iv) It is desirable to check the standardization regularly during a series of measurements.

Vernier Potentiometer The disadvantages of Crompton potentiometer are overcome in the Vernier potentiometer. Potentiometers discussed in previous sections are single-range potentiometers, usually constructed to cover a range of upto 1.8 V, and use two measuring dials. The Vernier potentiometer uses three measuring dials to include second measuring range of lower value and therefore, is also known as duo-range potentiometer. It makes use of Kelvin-Varley slide principle between the coarse and intermediate dials. This extends the reading accuracy by further decimal place. The instrument has two ranges: the normal range of 1.6 V down to 10 μV and a lower range of 0.16 V down to 1 μV.

Working In Brooks deflection potentiometer, an approximate balance is obtained and the greater portion of the voltage is read from the setting of the slide contacts. The remaining varying portion is measured from the deflection of a galvanometer calibrated in millivolt. For the galvanometer to give a deflection proportional to the out of balance voltage, it is essential that the galvanometer circuit resistance is constant. This is done by compensating resistance *R*, as shown in Fig. 3.26. The values of the compensating resistance are so chosen that the resistance of the potentiometer circuit as viewed from terminals *EF* remains constant irrespective of the position of the sliding contacts. This means that current through the galvanometer will always be proportional to the out of balance current, whatever may be the setting of the main dials. Thus, the galvanometer scale can be calibrated to read out of balance e.m.f. directly. The value of an unknown e.m.f. is obtained by adding the galvanometer reading to the main dial setting. The main dial setting is kept nearly equal to the e.m.f. being measured.

Self-balancing Potentiometer In industries, a continuous measurement of non-electrical quantity is required as the process is dynamic and a value of quantity is changing with time. A constant attention of an operator is a must in such situation. A self-balancing potentiometer helps in continuous measurement and hence eliminates the constant attention of operator. It is widely used in industry. In addition to its self- (automatic) balancing feature, it draws a curve of the quantity being measured with the help of recording mechanism. The curve can be displayed on the operator's desk for monitoring purposes.

Construction and Working Figure 3.27 shows the block diagram representation of a self-balancing potentiometer. In a self-balancing potentiometer, the unbalance e.m.f (which in normal potentiometer would produce a galvanometer deflection) is applied to an a.c. amplifier via a converter. The output of the amplifier is supplied to the control winding of an a.c. servomotor. This drives the motor to move the potentiometer slider to balance. The converter, inserted between the potentiometer output and the amplifier input, converts the d.c. unbalance voltage into an a.c. unbalance voltage. The

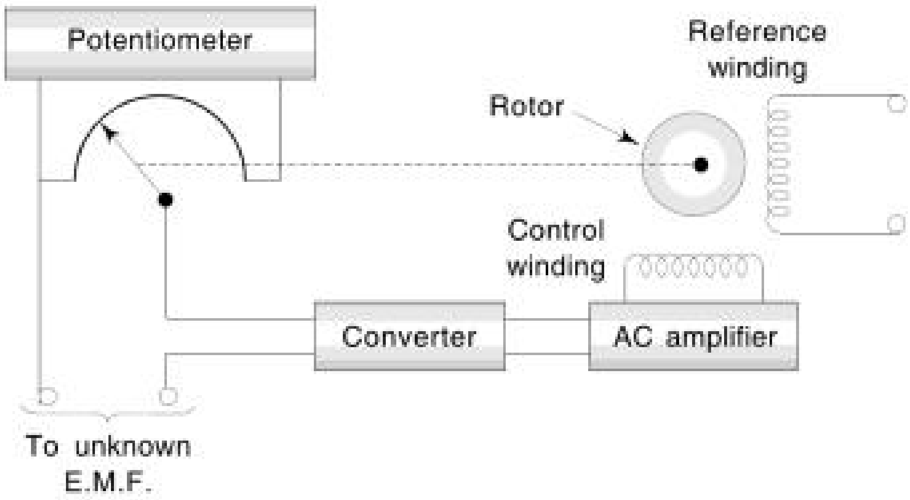


Fig. 3.27 *Block Diagram of Self-balancing Potentiometer*

Rectangular Co-ordinate Type Potentiometer Rectangular co-ordinate type potentiometer measures the unknown e.m.f. in terms of its regular co-ordinates. In this potentiometer, balance is obtained in terms of two voltages which are in quadrature (i.e. have a phase difference of 90°). Each of these voltages is varied in magnitude and a means is usually provided to adjust or check the quardrature phase relation. Since this type of potentiometer was developed by D.C. Gall, it is also known as *Gall co-ordinate potentiometer* or simply *Gall potentiometer*. Furthermore, since it was designed by H. Tensley and Co., the potentiometer is often referred *as Gall-Tensley potentiometer*.

Construction Figure 3.30 illustrates the schematic diagram of a Gall-Tinsley potentiometer. It consists of two slide-wires AB and CD with their currents I_1 and I_2 having mutual phase difference of 90°. The two currents are obtained from the single-phase supply through shielded isolating step-down transformers T_1 and T_2. Input transformer T_2 is connected to the input of the transformer T_1 through phase-splitting circuit. AB is the slide-wire for in-phase component V_1, while CD is the slide-wire for quardrature component V_2 as shown in Fig. 3.30.

Working As seen from Fig. 3.30, the Gall-Tinsley potentiometer is actually a combination of two potentiometers, one of which carries a current in-phase with the supply voltage and other carries a current in-quadrature with the supply

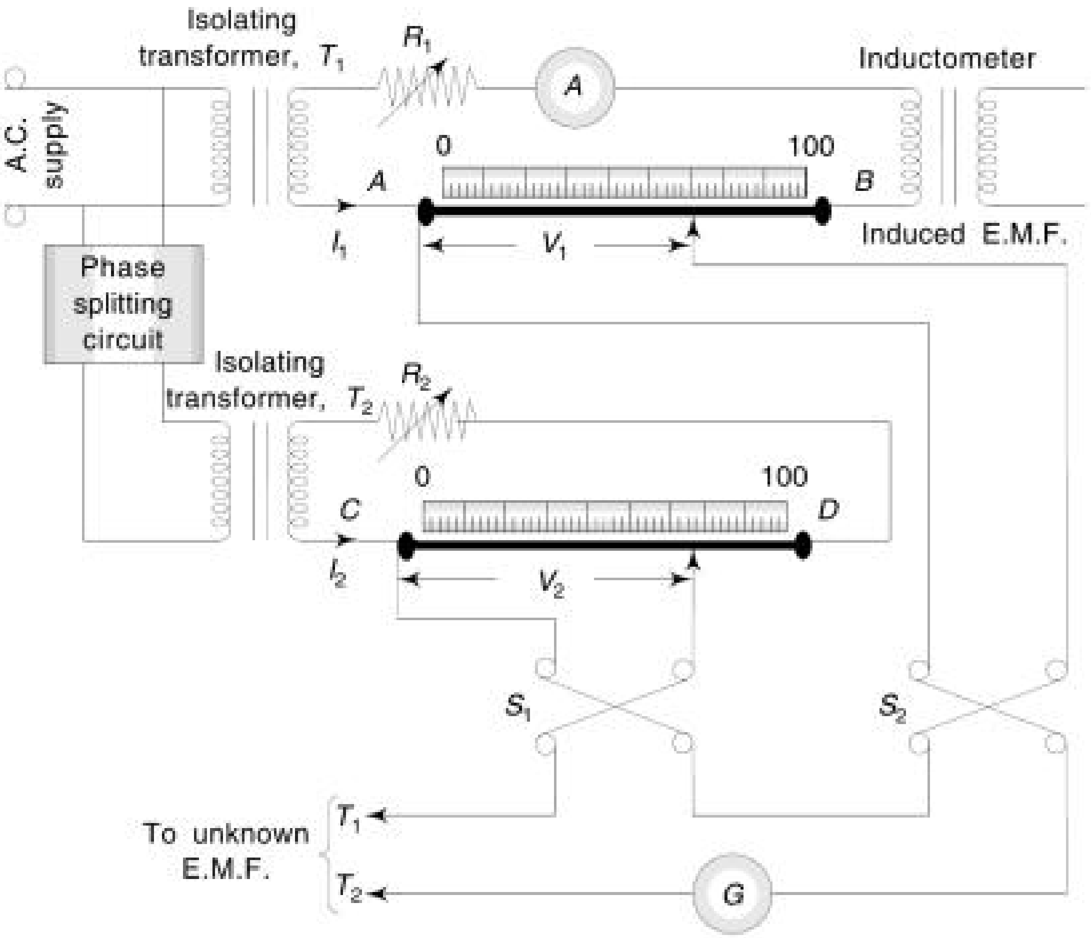


Fig. 3.30 *Gall-Tinsley Potentiometer*

(c) for proper ventilation
(d) to increase the deflection torque

7. A moving-coil instrument can be used to measure
   (a) low-frequency alternating current (b) high-frequency alternating current
   (c) direct current (d) d.c. an a.c. both
8. Electrostatic instruments are
   (a) voltage sensitive (b) current sensitive
   (c) both (a) and (b) (d) none of the above
9. Electrostatic intruments are most commonly used as
   (a) ammeters (b) voltmeters
   (c) wattmeters (d) all of the above
10. Wattmeters are
   (a) recording-type instruments (b) indicating-type instruments
   (c) both (a) and (b) (d) none of the above
11. The Ferranti-mercury motor meter is most commonly used as
   (a) watt-hour meter (b) kilowatt-hour meter
   (c) ampere-hour meter (d) none of the above
12. Megger is used for
   (a) testing the insulation resistance of a circuit
   (b) measuring the resistance of the order of mega ohms
   (c) testing the voltage and current
   (d) both (a) and (b)
13. A potentiometer is basically a
   (a) deflection as well as null-type instrument
   (b) deflection-type instrument
   (c) a digital instrument
   (d) null-type instrument
14. When a potentiometer is used for measurement of voltage of an unknown source, the power consumed in the circuit of the unknown source under null conditions is
   (a) small (b) very high
   (c) high (d) ideally zero
15. Standardization of potentiometer is done in order that they become
   (a) accurate and directly readable (b) accurate only
   (c) accurate and precise (d) precise
16. Brooks deflection potentiometer is used when the unknown voltage is
   (a) varying at a slow rate (b) constant
   (c) varying very rapidly (d) all of these

B. Fill-up the blanks:-

1. In a spring control instrument, the controlling torque is __________ to __________.
2. In a gravity control instrument, the controlling torque is proportional to __________.

Power in a d.c. circuit can be measured with the help of a voltmeter and an ammeter. As we know, the relationship between power, voltage, and current is given as

$$P = V \times I \tag{4.1}$$

But,

$$E = I \times R \tag{4.2}$$

Or,

$$R = \frac{V}{I} \tag{4.3}$$

Therefore,

$$P = I^2 \times R \tag{4.4}$$

and also

$$P = \frac{V^2}{R} \tag{4.5}$$

where,
P = apparent power in watts
V = circuit voltage in volts
I = current in amperes
R = resistance in ohms (Ω)

Power in an a.c. (alternating current) circuit at any instant is given as

$$P = v \times i \tag{4.6}$$

where,
p = instantaneous power
v = instantaneous voltage
i = instantaneous current

Thus, if both the current and voltage waves are sinusoidal, the current lagging in phase by an angle ϕ, then

$$v = V_{max} \sin \omega t$$

and

$$i = I_{max} \sin (\omega t - \phi)$$

The instantaneous power p of Eq. (4.6). is therefore given by

$$p = v \times i = V_{max} \sin \omega t \times I_{max}\, sin\, (\omega t - \phi)$$
$$= V_{max} I_{max} \sin \omega t \times sin\, (\omega t - \phi)$$

or, writing or θ for ωt,

$$p = V_{max} I_{max} \sin\theta \times sin\, (\theta - \phi)$$

The mean power is given as

$$P = \frac{1}{2\pi}\int_0^{2\pi} V_{\max} I_{\max} \sin\theta \sin(\theta - \phi) d\theta$$

$$= \frac{V_{\max} I_{\max}}{2\pi}\int_0^{2\pi} \frac{\cos\phi - \cos(2\theta - \phi)}{2} d\theta$$

$$= \frac{V_{\max} I_{\max}}{4\pi}\left[\theta\cos\phi - \frac{\sin(2\theta - \phi)}{2}\right]_0^{2\pi}$$

that would impair the accuracy. This is especially important when the power being measured is very low (a few microwatts), since then even a very slight amount of spurious energy reaching the bolometer will introduce a large error.

Advantages

- Both the barretter and thermistor are very sensitive elements, and can be used for measuring very small powers (as small as tens of microwatts).
- The barretter and thermistor are more stable with respect to time and exposure to overload than are detectors for very high frequencies, such as the silicon crystal, and in most circuits can be replaced without recalibration.
- They can also be used for monitoring large amounts of power by inserting a directional coupler between the bolometer element and the main radio-frequency system.

Disadvantages

- The thermistor element of the bolometer operates at lower temperatures and thus requires some compensation against ambient temperature changes.

Applications

- The bolometer method of measuring power is generally applied to measure very low powers (of the order of microwatts or milliwatts).
- Large power can also be measured with a bolometer using a directional-coupler arrangement.

4.2.2 Calorimeter Method

Working Principle In the calorimeter method of measuring radio-frequency power, the radio-frequency energy is converted into heat. This heat is absorbed in a fluid (usually water) that flows through the system, and then the temperature rise of the fluid is measured. The radio-frequency power may be absorbed directly in the calorimeter fluid, or the fluid may be used as a coolant for a resistive load of solid material. It is essential that all of the radio-frequency energy be transferred to the fluid, i.e., the system must have no radio-frequency leakage, either by radiation or in lossy joints. Likewise, the heat radiation from the fluid must be minimized until after the point in the system where the temperature measurement is made.

The power dissipated in a calorimeter can be calculated directly from the temperature rise, the specific heat of the fluid, and the rate of flow of the fluid, according to the relationship given as

$$P = 4.18 \times m \times s_p \times \Delta t \tag{4.9}$$

where P = power in watts

m = flow of fluid in grams per second (g/s)

s_p = specific heat in calories per °C

Δt = temperature rise in °C

Alternatively, the relationship between temperature rise and power dissipated can be determined experimentally by dissipating known amounts of a.c. or d.c. power in the calorimeter system.

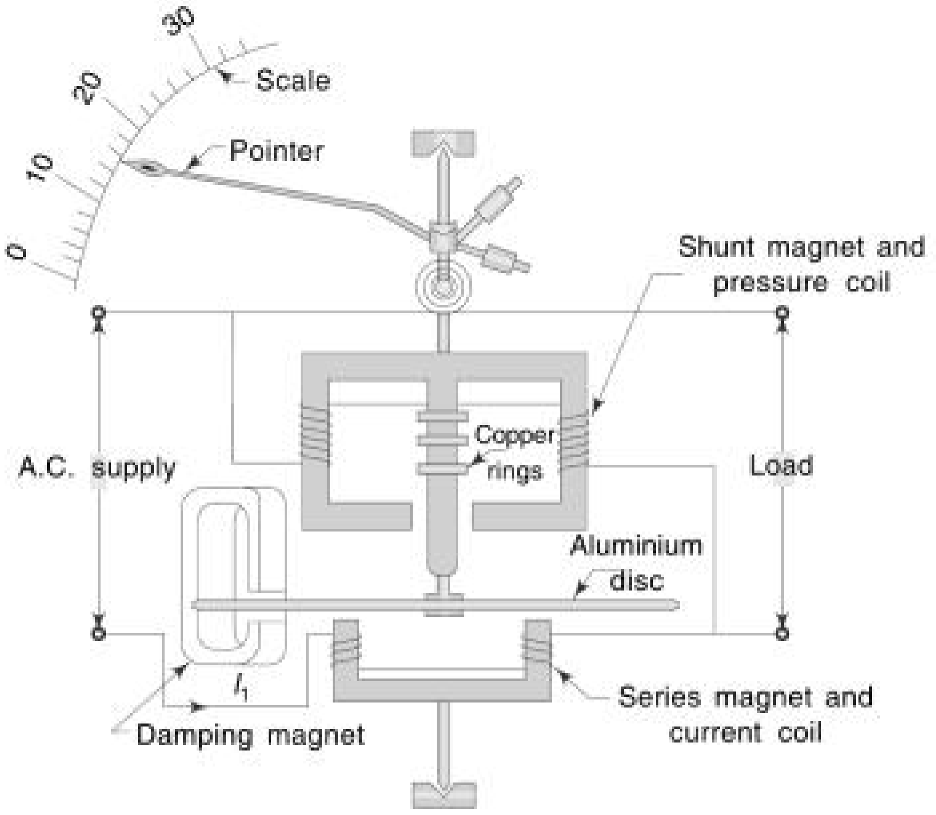


Fig. 4.5 *Induction Wattmeter*

Two or three copper rings are fitted on the central limb of the shunt magnet and can be adjusted to make the resultant flux in the shunt magnet lag behind the applied voltage by 90°. As shown in Fig. 4.5, two pressure coils are joined in series and are so wound that both send the flux through the central limb in the same direction. The series magnet also carries two coils joined in series and are so wound that they magnetize their respective magnetic cores in the same direction. Desired phase shift between the two magnet's fluxes can be obtained by adjusting the position of the copper shading rings.

The controlling torque in induction wattmeters is provided by a spring fitted to the spindle of the moving system which also carries the pointer.

The damping in these instruments is provided by the eddy current induced in the aluminium disc due to the fluxes produced by a permanent magnet.

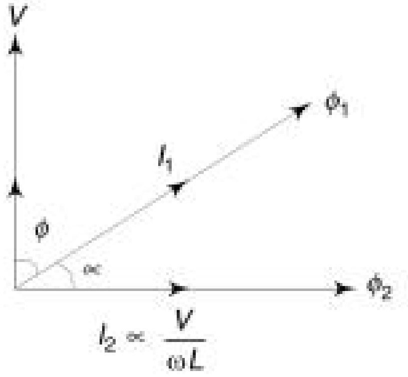


Fig. 4.6 *Vector Diagram Showing the Flux and Line Current*

Deflecting Torque As seen in Fig. 4.5, the current coil carries the line current I_1 so that the flux produced by it is directly proportional to the line current I_1 and is in phase with it, as shown in Fig. 4.6.

$$\phi_1 \propto I_1 \tag{4.12}$$

The pressure coil (or voltage coil) of the shunt magnet is made highly inductive, having an inductance 'L' Henry and negligible resistance. This is connected across the supply voltage V.

Hence, $$\phi_2 \propto I_2 \propto \frac{V}{\omega L}$$

(*b*) *Voltage coil capacitance error* In this type of error, the phase of the voltage coil current tends to *lead* the applied voltage instead of to lag behind as in case of voltage coil inductance. This causes the wattmeter to read low, on lagging power factor of the load, by increasing the angle between the load and voltage coil currents. The effect of frequency is to vary the phase angle between applied voltage V and voltage (pressure) coil current i_p, the angle increasing with increase in frequency.

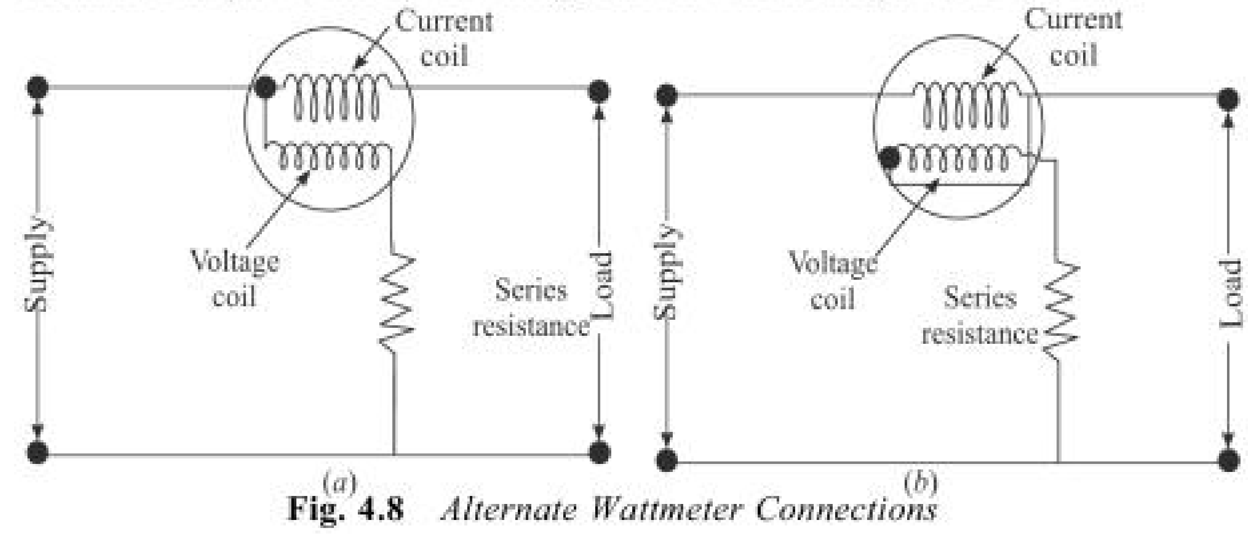
The voltage coil capacitance error is caused due to inter-turn capacitance in the high-value series resistance of the voltage coil circuit, which may have capacitance as well as inductance.

If the capacitive reactance of the voltage coil circuit is equal to its inductive reactance, there will be no error due to these effects since the two individual errors will neutralize one another.

(*c*) *Eddy current error* In this type of error, eddy currents induced in the solid metal parts of the instrument produced by the alternating magnetic field of the current coil, alter the magnitude and phase of this field. This results into error. The phase of the induced eddy e.m.f. (electromotive force) is 90° behind the inducing flux (main current in the current coil). The eddy current is practically in phase with its e.m.f., and this current sets up a magnetic field which, combined with that of the current coil, produces a resultant magnetic field, which is less than that of the current coil alone and which also lags behind the current coil field by a small angle.

This eddy current error is not easily calculable, and may be serious if care is not taken to ensure that any solid metal parts are well removed from the current coil. If the current coil is designed for heavy currents, it should consist of standard conductors in order to minimize the eddy currents flowing in the current coil itself.

Methods of wattmeter connection There are two methods of connecting a wattmeter in electrical circuit for power measurement, as shown in Fig. 4.8. In the first method, as shown in Fig. 4.8 (a), the voltage (or pressure) coil is connected on the supplied side of the current coil. In this connection, the voltage applied to the voltage coil is higher than that of the load on account of the voltage drop in the current coil. The wattmeter measures the power I^2R_c lost in the current coil. In the second method, as shown in Fig. 4.8 (b), the current coil carries the small current taken by the voltage coil, in addition to the load current. In this case, the wattmeter measures the power lost in the voltage coil as well as the power in the load.



(*a*) (*b*)

Fig. 4.8 *Alternate Wattmeter Connections*

braking, while M_2 is known as the driving magnet used for driving purposes. In between the poles of M_1 and M_2 is a hollow circular box B in which rotates the copper disc D. The rest of the space is filled up with mercury which exerts considerable upward thrust on the disc, thereby reducing the pressure on the bearings. The spindle is so weighted that it just sinks in the mercury bath. A worm cut in the spindle, at its top, engages the gear wheels of the recording mechanism (Fig. 4.12).

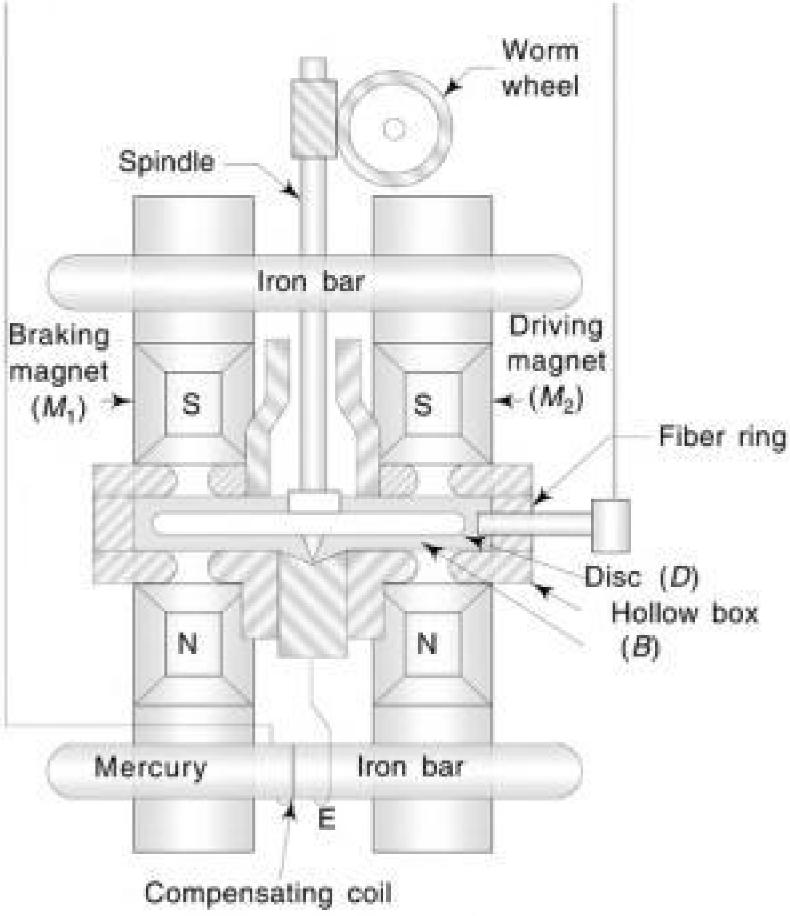


Fig. 4.12 *Ferranti Mercury Motor Meter*

Working The current to be measured is led into the disc by a contact C, through the mercury, and out through the supporting screw L. Since the field is vertically upward and the flow of current through the disc is radial, the disc will rotate as a motor under the influence of the right-hand magnet (i.e. driving magnet) M_2 and will act as a generator and have eddy currents induced in it by the left-hand magnet (i.e. braking magnet) M_1. The braking magnet M_1, therefore, provides the necessary controlling torque. Figure 4.13 illustrates the operating principle.

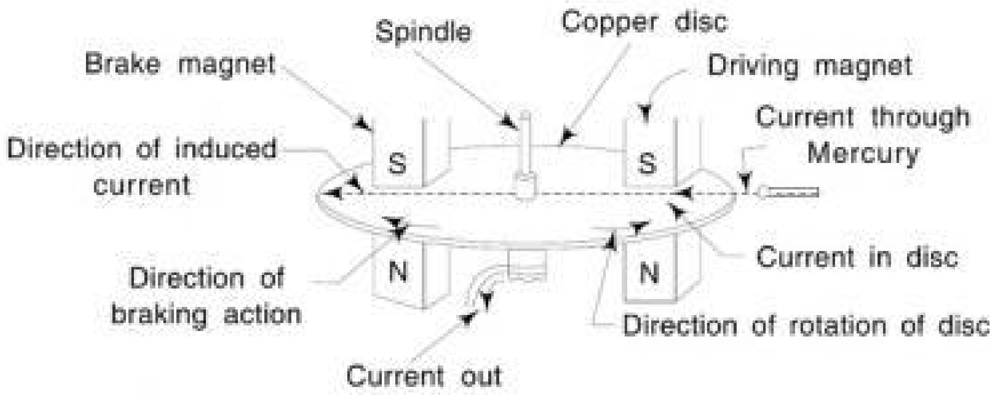


Fig. 4.13 *Illustrating the Principle of the D.C. Ampere-hour Meter*

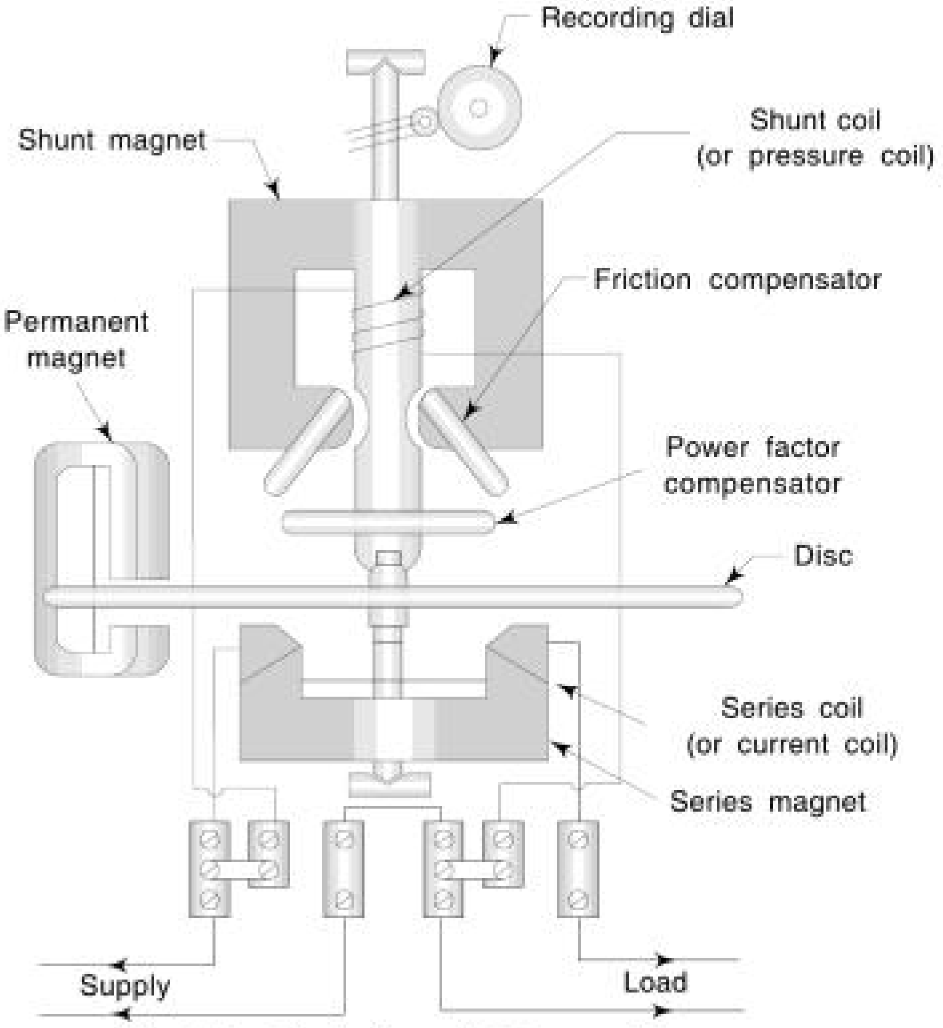


Fig. 4.15 *Single-phase A.C. Energy Meter*

exactly to 90°, a closed coil or loop is placed on the core of the shunt electromagnet to embrace the path of the flux which passes across the disc. Thus loop may be in the form of a short-circuited band capable of being adjusted in space in the flux path, or a fixed loop with its ends terminating in the adjsutable resistance (Fig. 4.15).

(b) Three-Phase Energy Meter Three-phase energy meters are used to measure power in three-phase circuits. They consist of two single-phase energy meters working on two discs fixed to the same spindle (Fig. 4.16). For the correct working of these meters, the elements of two single-phase energy meters are connected in their proper phase sequence. The operating principle of 3-phase energy meters is the same as that of single-phase energy meters. Figure 4.16 shows the connection diagram of a 3-phase energy meter.

Errors and Their Compensation in Induction-Type Energy Meters

Phase Errors Normally, the flux due to the shunt magnet does not lag behind the supply voltage by exactly 90° due to the fact that the coil has some resistance. Therefore, the torque is not zero at zero power factor. This is known as phase error and is compensated by means of an adjustable copper band placed over the central limb of the shunt magnet. Due to this reason, the shading ring is known as the power factor compensator.

C. State True/False:-

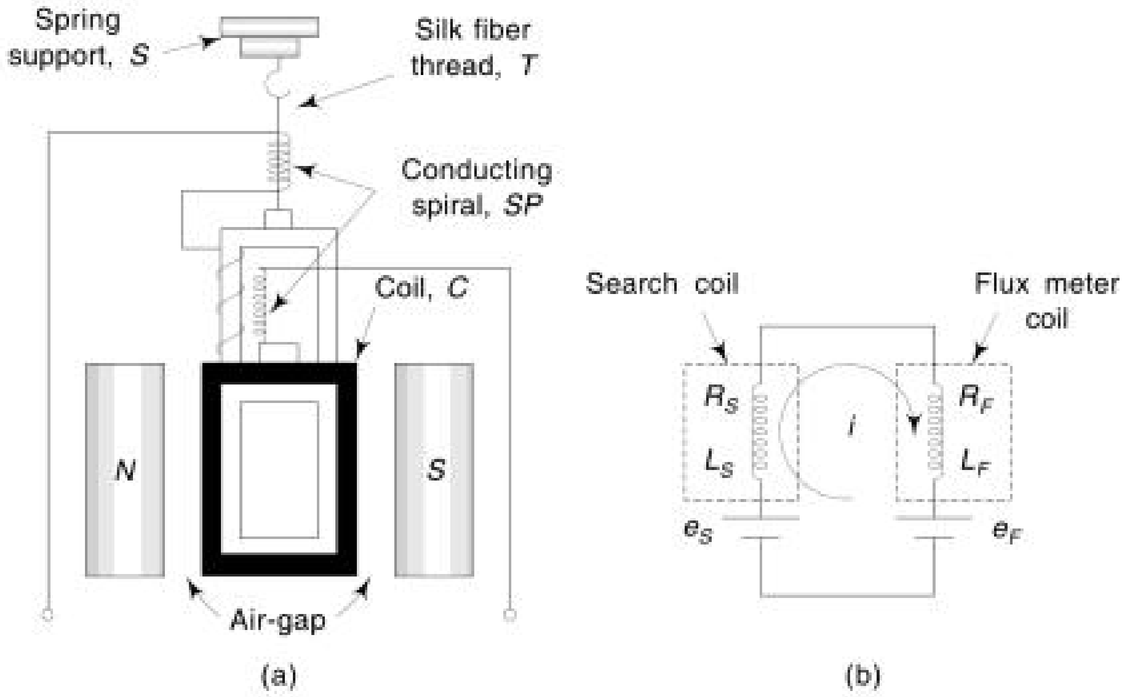
1. In a single-phase a.c. energy meter, there is no creeping error.
2. Barretters are normal resistive elements with a positive coefficient of resistance.
3. Thermistors are compounded of metallic oxide materials possessing a positive temperature coefficient.
4. The bolometer method of power measurement is used for very high powers whereas the calorimeter method is used for very low power measurement.
5. The power dissipated in a calorimeter is inversely proportional to the specific heat of the fluid.

REVIEW QUESTIONS

1. Describe with a neat sketch the construction and principle of the working of single-phase and three-phase energy meters.
2. What is creeping of an energy meter?
3. What are the different types of errors in a single-phase energy meter? How can they be overcome?
4. Explain the working of the following power measuring instruments with neat sketches:
   (a) Bolometer (b) Calorimeter
   Write their advantages, disadvantages, and specific applications.
5. What is a wattmeter? What are the different types of wattmeters? Explain with a neat sketch its working, advantages, and disadvantages.
6. What is an energy meter? What are its different types? Describe their working with neat sketches.
7. Describe the working of a.c. induction energy meters.
8. What is a dynamometer instrument? Discuss its construction and operation. Show the connections of a dynamometer wattmeter. Derive an expression for its deflecting torque.
9. Discuss the principle of an induction wattmeter. Derive an expression for its deflecting torque.
10. Describe the constructional details of a single-phase induction-type energy meter.
11. Explain the working of different types of wattmeter methods of power measurement in single-phase and three-phase electrical circuits.
12. Explain how the following adjustments are made in a single-phase induction type energy meters:
    (a) Lag adjustment (b) Creep
    (c) Friction compensation (d) Speed compensation
    (e) Temperature compensation (f) Light load adjustment

5.3.1 Construction

The construction of a flux meter is shown in Fig. 5.1(a). It consists of a coil *C* of small cross-section suspended from a spring support *S* by means of a single silk thread *T* and hangs with its parallel sides in the narrow air-gap of a permanent magnet system. The coil moves in this narrow air-gap. The current is led into the coil *C* by spirals *SP* of very thin, annealed silver strips. This reduces the controlling torque to minimum. Flux meter is fitted with a pointer attached to the moving system and a scale. The scale is graduated in terms of flux-turns. Since, this flux meter was designed by Grassot, hence it is also referred as *Grassot flux meter*.



(a) (b)

Fig. 5.1 *(a) Flux Meter, (b) Equivalent Circuit for Flux Meter*

In modern flux meters the coil is fitted with pivots and mounted in jewelled bearings, the current being led into the coil by fine ligaments. This form of construction is more robust than suspended instruments.

5.3.2 Working Principle

Assume that the controlling torque is negligibly small and also that air damping and friction are negligible. In this case, the flux meter would remain in its deflected position indefinitely. Actually the pointer returns very slowly to zero, but readings may be taken by observing the difference in deflection at the beginning and end of the change in flux to be measured without waiting for the pointer to return to zero, the scale being uniform. As shown in Fig. 5.1(b), the resistance R_S of the search coil circuit connected to the flux meter should be fairly small because variation in this resistance of several ohms usually have a negligible effect upon deflection.

If Φ_1 and Φ_2 are the inter-linking fluxes at the beginning and at the end of the change in flux to be measured, and θ_1 and θ_2 are the corresponding deflection, then

A_S = cross-sectional area of search coil
A = cross-sectional area of specimen

This modified value of flux density B derived in Eq. (5.14) is often referred as the *correction for air flux*.

Advantages Following are the advantages of the above method of flux density measurement:

(i) Maximum sensitivity can be used in all readings of the instrument.
(ii) Measurements obtained from ring specimen are more accurate.

Disadvantages Following are the disadvantages of the above method of flux density measurement:

(i) It is more difficult to prepare ring specimen.
(ii) It is also difficult to wind with the magnetizing coil winding.

5.4.2 Measurement of Magnetizing Force H

The magnetizing force H of a constant magnetic field can be measured indirectly by a ballistic galvanometer and a search coil. The value of H inside a specimen can either be inferred from calculations involving data of magnetizing coil and the specimen or from measurements made outside the specimen.

Construction A schematic diagram of measurement of magnetizing force in rod (bar) specimen is shown in Fig. 5.3. It consists of a search coil C_S which is also called an H coil. Magnetizing winding, also called B coil, surrounds the specimen. A ballistic galvanometer is connected across the search coil. A reversal (change-over) switch S_1, is connected with a d.c. (battery) power supply.

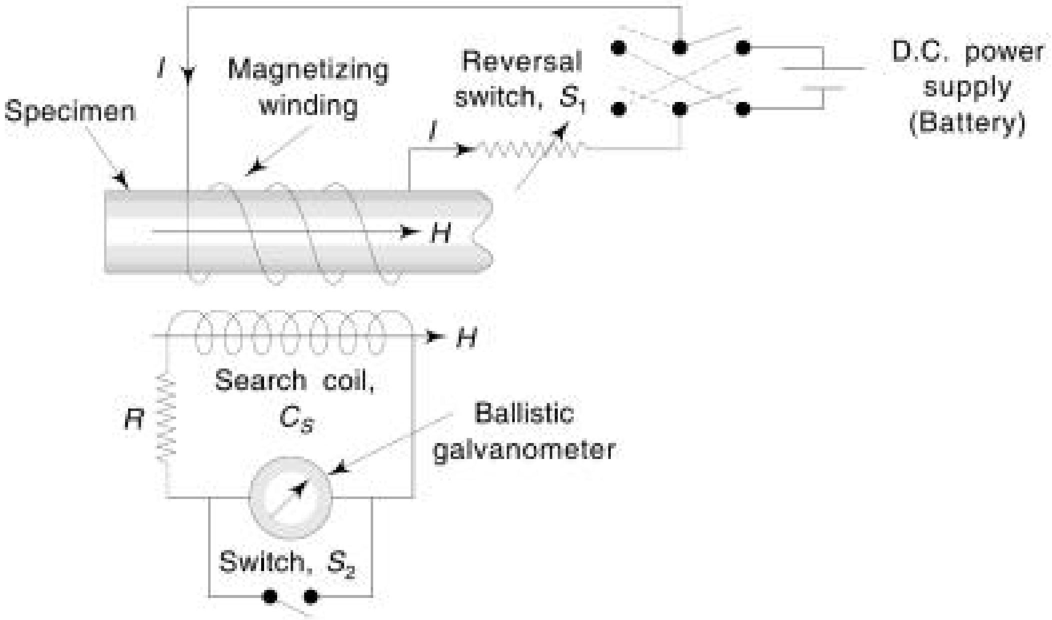


Fig. 5.3 *Measurement of Magnetizing Force H*

Working Principle The value of H inside a specimen can be calculated from the formula given as

$$H = \frac{NI}{l} \text{ Ampere-turns (AT)/meter} \tag{5.15}$$

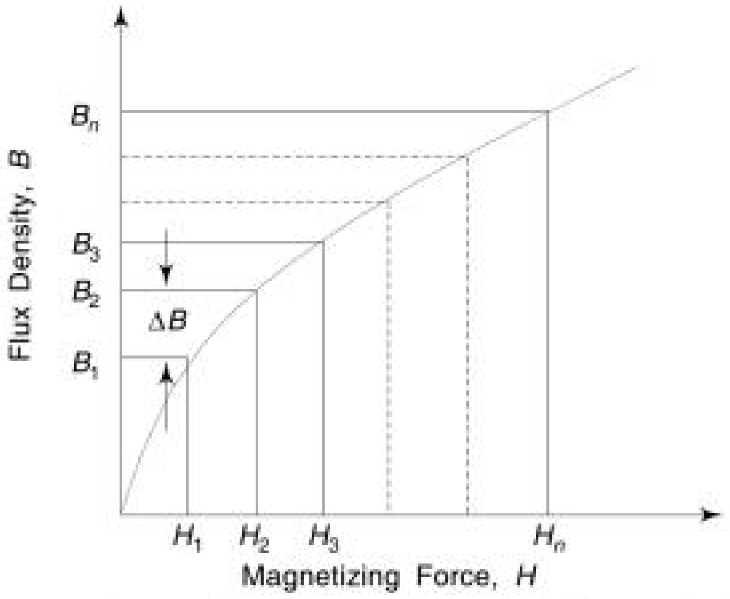


Fig. 5.6 *Plotting of B-H Curve Using Step-by-step Method*

causes heat loss in the magnetic material. Area of hysteresis loop measures the energy in Joules dissipated due to hysteresis which appears in form of heat. Therefore, the hysteresis loss is the product of the area of hysteresis loop and the frequency.

5.5.1 Methods for Determination

Similar to the B-H curve, following are the two methods for the determination of hysteresis loop:

(i) Method of Reversal
(ii) Step-by-step Method

Method of Reversal This method of determination of hysteresis loop can be accomplished by means of several steps. The change in flux density B measured at each step is the change from the maximum value of flux density $+B_{max}$ down to some lower value. But, before the next step is commenced, the specimen is passed through the remainder of the cycle of magnetization back to the maximum value of flux density $+B_{max}$. Thus, the cyclic state of magnetization is preserved. Reversal method of hysteresis loop determination is shown in Fig. 5.7.

The circuit for the determination of hysteresis loop through reversal method is the same as shown in Fig. 5.2 for the method of reversal, except that the dc supply to the magnetizing coil is modified by providing two variable resistances and a switch S_4, as shown in Fig. 5.7. The variable resistances R_1, R_2 are connected in the magnetizing coil circuit for adjusting the value of magnetizing current I. The specimen is first demagnetized. The value of the magnetizing force H_{max}, corresponding to the maximum value flux density B_{max}, is obtained from B-H curve as determined in Section 5.4. With the switch S_4 closed, the resistance R_1 is adjusted to regulate the magnetizing current which produces maximum magnetizing force H_{max} (as per Eq. (5.15)). The variable shunt resistance R_2 is adjusted to such a value that a suitable reduction of the magnetizing current is obtained when switch S_4 is opened.

With the reversal of current, the change of flux linkage

$$= 2 \times 400 \times 1.6 \times 10^{-3}\ \mu_r \times 5 \times 10^{-4}$$

$$= 6.4 \times 10^{-4} \mu_r$$

Hence, emf induced in the secondary

$$e = \frac{2N\Phi}{t} = \frac{6.4 \times 10^{-4}\ \mu_r}{t}$$

where, t is the time

and current i will be given as

$$i = \frac{2N\Phi}{Rt} = \frac{6.4 \times 10^{-4}\ \mu_r}{200 \times t}$$

But, quantity of electricity is also given as

$$e = it$$

$$= \frac{6.4 \times 10^{-4}\ \mu_r}{200 \times t} \times t$$

$$= 32 \times 10^{-7}\ \mu_r$$

But, the quantity of electricity indicated by the galvanometer is 3000×10^{-6} coulomb.

$$\therefore \quad 32 \times 10^{-7} \mu_r = 3000 \times 10^{-6}$$

or, $$\mu_r = 937.5$$

Example 3 *A moving coil ballistic galvanometer of 200 ohm resistance gives a throw of 100 divisions when the flux through a search coil to which it is connected is reversed. Find the flux density, given that the galvanometer constant is 120 μC per scale division and the search coil has 1500 turns, a mean area of 60 cm² and a resistance of 30 Ω.*

Solution It is given that,

Number of turns in the search coil	$N = 1500$ ampere-turn (AT)/m
Cross-sectional area of search coil	$A = 60\ \text{cm}^2 = 60 \times 10^{-4}\ \text{m}^2$
Galvanometer sensitivity (a constant)	$K = 120\mu\text{C} = 120 \times 10^{-6}$ C/division
Combined resistance of the circuit	$R = 200\ \Omega + 30\ \Omega = 230\ \Omega$
Galvanometer throw (deflection)	$\theta = 100$
Permeability of specimen in air	$\mu_0 = 4\pi \times 10^{-7}$ Henry/meter

Now, flux density B is given as

$$B = \frac{RKq}{2NA}\ \text{Wb/m}^2$$

or, $$B = \frac{230 \times 120 \times 10^{-6} \times 100}{2 \times 15000 \times 60 \times 10^{-4}}\ \text{Wb/m}^2$$

$$B = 0.153\ \text{Wb/m}^2$$

Example 4 *For calibration of a flux meter, it is connected to the secondary of an air-cored solenoid placed at its centre. The solenoid is 2 meter long and is wound with 1000 turns. The secondary has 600 turns and mean area of 6 cm². When a current of 5 amps in the primary is reversed, there is a deflection of 30 scale divisions in the flux meter. Calculate the constant of the flux meter in flux linkage per scale division.*

Solution It is given that,

Number of turns in the primary winding	$N_1 = 1000$ ampere-turn (AT)/m
Number of turns in the secondary winding	$N_2 = 600$ ampere-turn (AT)/m

4. Iron losses or core losses are determined by
   - (a) alternating current test
   - (b) direct current test or ballistic test
   - (c) steady state test
   - (d) none of the above
5. The value of permeability of a magnetic material in air is
   - (a) $4\pi \times 10^{-7}$
   - (b) $4\pi \times 10^{-9}$
   - (c) $2\pi \times 10^{-7}$
   - (d) $\pi \times 10^{-7}$

B. Fill-up the blanks:-

1. The value of permeability of a magnetic material in air is ______.
2. The ballistic galvanometer is used to measure ______.
3. Flux meter is a special type of ballistic galvanometer in which the ______ torque is very small and ______ is very heavy.
4. It is more difficult to prepare ______ specimen than ______ specimen.
5. The method of determination of hysteresis loop can be accomplished by means of the two steps called (a) ______ and (b) ______.

C. State True/False:-

1. The flux density of magnetic material is directly proportional to the magnetizing force.
2. Steady state tests are used for the determination of *B-H* curve.
3. Alternating current tests are used for the determination of iron losses or core losses in strip material when it is subjected to alternating field.
4. Bar specimens are much easier to construct than ring specimen.
5. The sensitivity of flux meter is inferior to the ballistic galvanometer.
6. The literary meaning of term hysteresis is to *lag behind*.
7. In magnetic materials, the magnetizing force always lags behind the flux density.
8. The flux meter has advantage over galvanometer because the length of time taken for the change in the flux producing the deflection need not be small.
9. The ballistic galvanometer is used to measure a quantity of electricity passed through it.
10. The flux density inside a specimen is determined by winding a *H*-coil over the specimen.

REVIEW QUESTIONS

1. An iron ring of 5 cm^2 cross-section with mean diameter of 30 cm is wound with a magnetizing winding of 200 turns. A search coil wound on specimen and with 400 turns of thin wire is connected to a ballistic galvanometer having a constant of 1 μC per division. The total resistance of the galvanometer is 3000 Ω. On a reversal of 10 A current in the magnetizing coil, the galvanometer gives a throw of 100 divisions. Calculate flux density in the specimen and the relative permeability at this flux density.
2. A flux meter is connected to a search coil having 600 turns and a mean area of 10 cm^2. The search coil is placed at the centre of the solenoid 1 meter long, wound with 700 turns. When a current of 4 A is reversed, there is deflection of 30 scale divisions. Calculate the calibration in flux linkages per scale division.

(ii) Low Power Consumption Electronic voltmeters present very high resistance across the circuit whose voltage is to be measured. Thus, they consume very little or practically no power from the circuit whose voltage is being measured.

(iii) High FrequencyRange The response of electronic voltmeters can be made practically independent of frequency within wide limits. They can be calibrated at a low frequency and then can be used upto very high radio frequencies without any correction being made. Some electronic voltmeters permit the measurement of voltage from d.c. to frequencies of the order of hundreds of MHz.

(iv) Low Input Capacitance Electronic voltmeters have very low input capacitance that may be of the order of a few pico Farad (pF).

(v) No Loading Errors Electronic voltmeters avoid the loading errors by supplying power required for measurement by using external circuits like amplifiers. The amplifiers not only supply power required for the operation but also make it possible for low level signals. These low level signals produce a current less than 50 A for full scale deflection. This full-scale deflection, otherwise, cannot be detected in the absence of amplifiers.

The transistor voltmeter (TVM), also called the electronic voltmeter (EVM), has the following advantages over vacuum tube voltmeters (VTVM):

(i) It requires no warm-up time because of the absence of a heater element.
(ii) Transistorized instruments are portable and are, thus, well suited for field work.
(iii) Power consumption is negligible.

But, the input resistance of transistor is low compared to a vacuum tube and therefore, TVM is used in conjunction with field effect transistor (FET) that has very high input impedance.

Analog electronic voltmeters are generally of the following types:

(i) AC Electronic voltmeters (ACEVM)
(ii) DC Electronic voltmeters (DCEVM)

6.2.4 A.C. Electronic Voltmeter (ACEVM)

Construction and Working An A.C. electronic voltmeter (ACEVM) is used to measure a.c. (alternating current) voltages. In this case, a.c. voltage to be measured is first conditioned with the help of a switching and amplification circuit using a wide-band amplifier. The output of this amplifier is then rectified (converted into d.c.) using either a half-wave or full-wave rectifier. The resulting d.c. (direct current) from the rectifier is used to operate a D'Arsonval type or permanent magnet moving-coil (PMMC) instrument as shown in the form of block diagram in Fig. 6.1.

The input signal conditioning for a.c. voltage measurements includes both attenuation and amplification. Figure 6.2 shows typical input switching and ranging circuits for an a.c. voltage instrument. It consists of an input coupling capacitor C_1 which blocks the d.c. portion of the input signal so that only the a.c.

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some cases after the amplification (as shown in Fig. 6.4(c) & (d)). This is the simplest type of diode rectifier and consists of single diode *D* for half-wave rectification or diode bridge for full-wave rectification and a high resistance *R* connected in series. If the rectification is to be done before amplification then the average value of the half-wave or full-wave rectifiers is developed across the resistance *R* and applied to the input of the d.c. amplifier, as shown in Fig. 6.4(a) and (b). The output of the amplifier is fed to a moving coil (PMMC) instrument.

In case the rectification is to be done after amplification then the amplified average value is supplied to the rectifier circuit of the half-wave or full-wave rectifiers, as shown in Fig. 6.4(c) and (d). The output of the rectifier is fed to a moving coil (PMMC) instrument.

The average-responding a.c. electronic voltmeters are well suited for sinusoidal waveforms and not for non-sinusoidal waveforms. Indeed, even small amounts of odd harmonic distortion of a sine wave input can cause large errors in the readings of an average-responding a.c. electronic voltmeter.

Advantages Following are the advantages of *average-responding* a.c. electronic voltmeter:

(i) This type of instruments are well suited for sinusoidal waveforms.
(ii) This instrument is very simple to use.
(iii) It has high input resistance.
(iv) It has low power consumption.
(v) It has evenly divided rms scale.
(vi) This may also be used for d.c. measurement.

Disadvantages Following are the disadvantages of *average-responding* a.c. electronic voltmeter:

(i) This type of instruments are not suitable for precision measurements when non-sinusoidal waveforms are applied.
(ii) At radio frequencies the distributed capacitance of the series resistance affect the reading of the instrument.
(iii) Due to non-linear volt-ampere (*V/I*) characteristics at lower voltage range, the reading of the meter is not accurate at lower voltage.
(iv) Even small amounts of odd harmonic distortion of a sine wave input can cause large errors in the readings.

Peak-responding A.C. Electronic Voltmeter

Construction and Working *Peak-responding* a.c. electronic voltmeters are used for measuring peak value of a.c. voltage. It consists of a storage capacitor *C* in parallel with resistance *R*, as shown in Fig. 6.5. The input a.c. voltage is half-wave rectified using diode. Initially, the capacitor *C* is uncharged. During first positive quarter cycle of the input sine waveform diode *D* is forward biased and starts conducting. The value of input voltage increases upto the positive peak (as shown in Fig. 6.3) during this period. The capacitor *C*, therefore, starts getting charged immediately and is fully charged to the peak value at the end of the first

Direct-coupled DCEVM

Construction and Working A schematic circuit diagram of a *direct-coupled d.c. amplifier d.c. electronic voltmeter* is shown in Fig. 6.7 with field effect transistor (FET) input. It consists of a range switch (also called input attenuator) which attenuates the d.c. input voltage V_{idc} to a voltage that can be accommodated by the d.c. amplifier. A FET T_1 is used to serve as source follower at input stage to obtain a high input impedance. Field effect transistor T_1 effectively isolates the meter circuit from the circuit under measurement.

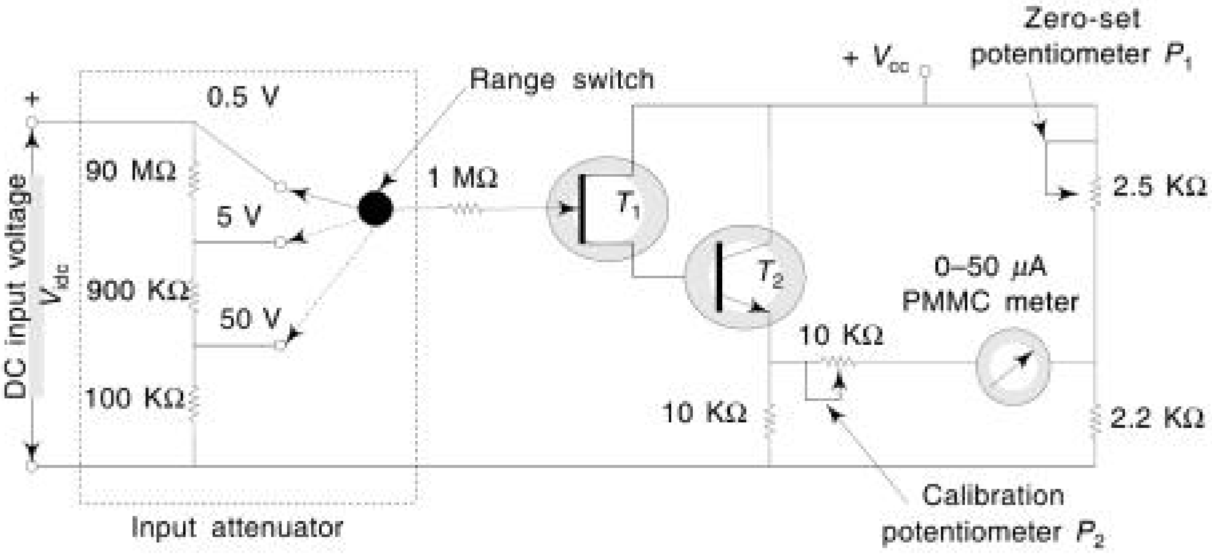

Fig. 6.7 *Direct-coupled DC Amplifier Electronic Voltmeter*

The d.c. input voltage V_{idc} is applied to the input attenuator, an input voltage divider which permits a maximum voltage of 0.5 V to be applied to the gate of n-channel FET T_1, without causing distortion. The FET T_1, serving as source follower, is directly coupled to an emitter follower (npn-type transistor T_2). The transistor T_2 is one arm of the bridge circuit whose remaining arms consist of the 10 KΩ emitter resistor of T_2 and the 2.5 KΩ *zero-set* potentiometer P_1 in series with the 2.2 KΩ resistor. Bridge balance, or zero meter current, is obtained by adjusting *zero-set* potentiometer P_1. Full-scale calibration is adjusted by the 10 K calibration potentiometer P_2, in series with the 50 μA meter movement.

Advantages of Direct-coupled DCEVM Following are the advantages of direct-coupled DCEVM:

(i) The input impedance of direct-coupled d.c. amplifier DCEVM is 10 M Ω, which is sufficiently high to ignore any possible loading effects on the circuit under measurement.

(ii) Direct-coupled d.c. amplifier DCEVM decreases the amount of power drawn from a circuit under test by increasing the input impedance using an amplifier with unity gain.

(iii) Direct-coupled d.c. amplifiers are economical and are commonly found in low-priced d.c. voltmeters.

6.3 DIGITAL ELECTRONIC VOLTMETER (DVM)

A *digital electronic voltmeter*, also called digital voltmeter (DVM), measures and displays d.c. or a.c. voltages as discrete numerals instead of a pointer deflection on a continuous scale as in analog electronic instruments. In 1965, the first digital voltmeter was marketed by M/s Non Linear Systems Inc. This meter scaled inputs and then digitized them, showing the results in a numeric digital display. The block diagram of a simple digital voltmeter is shown in Fig. 6.9.

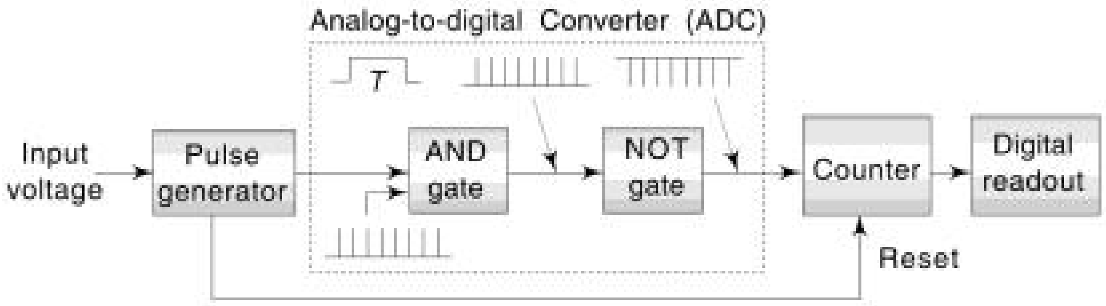

Fig. 6.9 *A Block Diagram of Digital Voltmeter (DVM)*

As shown in Fig. 6.9, a pulse generator generates a pulse whose width is directly proportional to the input voltage. The output of the pulse generator is one of the inputs of an AND gate circuit. The other input signal to the AND gate is a train of pulses. The output of the AND gate is, thus, a positive trigger train of duration *T* second and the NOT circuit changes it into a negative trigger train. The counter, then, starts counting the number of triggers in *T* seconds which is proportional to the voltage to be measured. The counter can be calibrated in volt to read the measured input voltage.

Thus, it can be observed from the above description that the digital voltmeter described above, is basically, an analog-to digital converter (ADC) which converts an analog signal into a train of pulses, the number of which is proportional to the magnitude of the input voltage. With appropriate signal conditioning of the input voltage, DVM can be used to measure many electrical and physical quantities such as a.c. voltages, d.c. and a.c. current, resistance, temperature, pressure, etc.

Digital voltmeters can be classified into the following broad categories on the basis of analog-to-digital converter (ADC) used:

(i) Ramp-type DVM
(ii) Integrating-type DVM
(iii) Continuous-balance or Servo-balance DVM
(iv) Successive-approximation DVM

6.3.1 Ramp-type DVM

Working and Construction The operating principle of the *ramp-type DVM* is based on measurement of the time taken by the DVM for a linear ramp voltage to rise from 0 V to the level of the input voltage, or to decrease from level of the

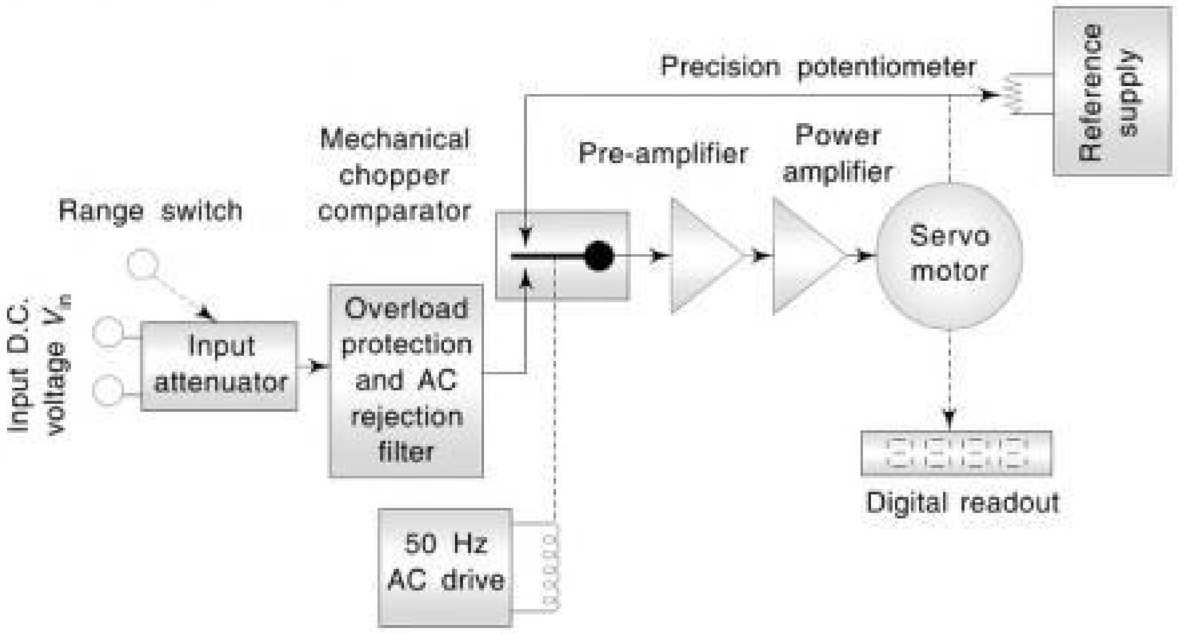

Fig. 6.12 *Block Diagram of Continuous-balance or Servo-balance DVM*

signal is a function of the difference in magnitude and polarity of the d.c. voltages connected to the opposite side of the chopper. The square-wave signal is amplified by a high-impedance, low-noise pre-amplifier and fed to a power amplifier. The power amplifier has special damping to minimize overshoot and hunting at the null position.

The servo-motor, on receiving the amplified square-wave difference signal, drives the arm of the precision potentiometer in the direction required to cancel the difference voltage across chopper comparator. The servo-motor also drives a drum-type mechanical indicator that has the digits 0 to 9 imprinted about the periphery of its drum segments. The position of the servo-motor shaft corresponds to the amount of feedback voltage required to null the chopper input, and this position is indicated by the drum-type indicator. The position of the shaft, therefore, is an indication of the magnitude of the input d.c. voltage. The continuous-balance DVM uses the principle of balancing the input voltage against the internally generated reference instead of sampling, because of the different mechanical movements involved in the mechanism such as positioning of the potentiometer arm and the rotation of the indicator mechanism.

Advantages of Continuous-balance or Servo-balance DVM Following are the advantages of continuous-balance or servo-balance DVM:

(i) It is a low cost instrument that provides excellent performance.

(ii) The accuracy of this DVM is quite satisfactory, usually of the order of 0.1% of its input d.c. voltage.

(iii) It has high input impedance, of about 10 MΩ.

6.3.4 Successive-approximation DVM

Working and Construction In successive-approximation DVM, successive-approximation converter is used as analog-to-digital converter (ADC) to perform

DMMs and VMMs can be evaluated on

(i) a variety of features, such as accuracy, resolution, reading rates, and measurement ranges

(ii) additional functions, such as frequency, period, temperature, minimum/maximum, and diode test

(iii) math capabilities, such as relative, percent, or standard deviation readings.

6.5.1 Construction and Working

A basic block diagram of a virtual multimeter (VMM) is shown in Fig. 6.15. All DMMs and VMMs share the same architecture. The architecture is divided into three main components namely, front-end signal conditioning, Analaog-to-digital (A/D) converter, and processor and display. Like traditional DMMs, VMMs have front-end analog measurement circuitry to interface to real-world signals.

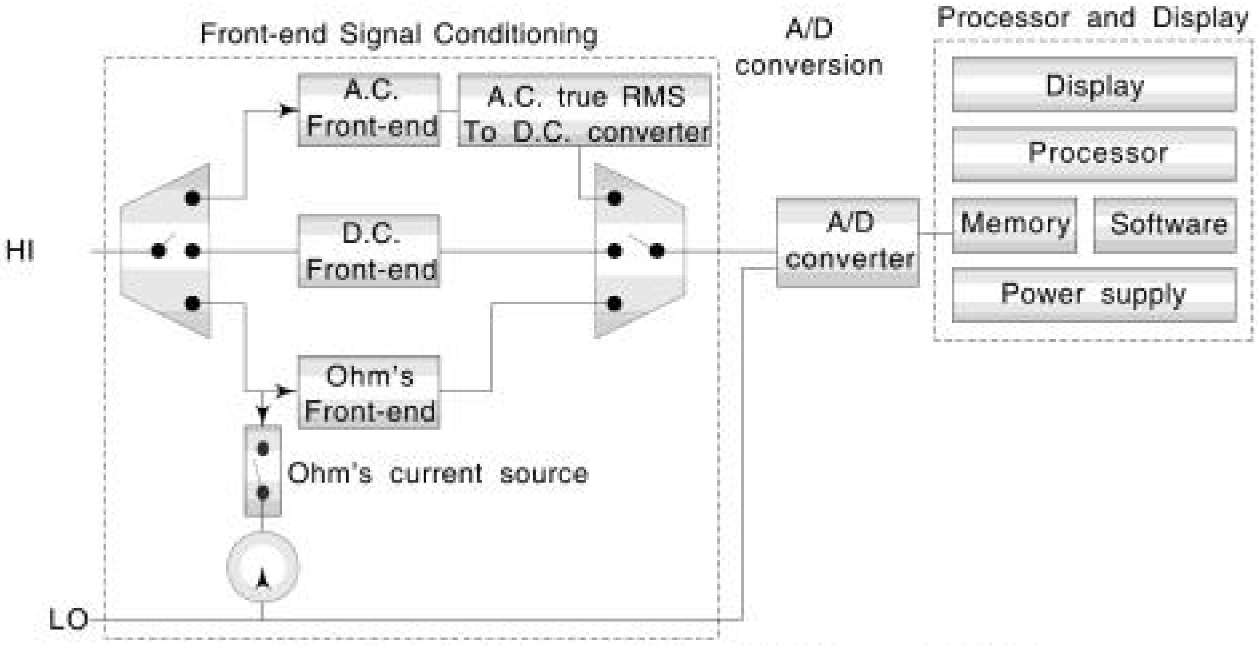

Fig. 6.15 *Architecture of Virtual Multimeter (VMM)*

The A/D converter inside the VMM converts analog input signals to digital values. It is the primary component that affects reading speed, resolution, accuracy, and normal-mode rejection. Sophisticated VMMs are multi-slope integrating A/D circuits or sigma-delta A/D converts to achieve high resolution and accuracy. A hardware A.C. conversion circuit is built on the dedicated multimeter boards in the signal-conditioning front end to convert A.C. signals to D.C. voltages to be measured by the A/D converter. The A.C. converter may be either an averaging type or a True-rms (T_{rms}) converter. Both averaging and T_{rms} converters will give the same output for sine waves, but signals other than sine waves produce an error when measured with an average-based meter. For irregular waveforms, a T_{rms} converter gives more accurate results. VMMs built with general-purpose A/D boards, do not have specialized hardware A.C. conversion circuitry. Rather, they use software-based T_{rms} A.C. conversion algorithms that execute on the computer itself.

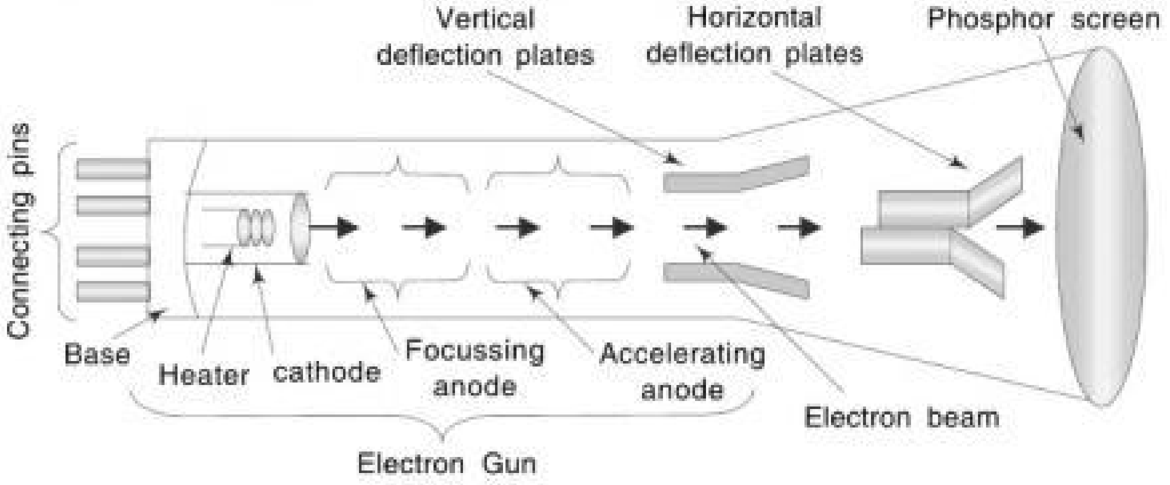

Fig. 6.18 *Schematic Diagram of CRT*

electrons which are directed and accelerated at high velocity. This focussed beam of electrons strikes the fluorescent screen with sufficient energy to cause a luminous spot on the screen. The electron gun consists of a heater, cathode, a focussing anode and an accelerating anode. Electrons are emitted from the indirectly heated cathode, which is coated with a layer of barium and strontium oxide. Cylindrical shape of the cathode is used to obtain high emission of electrons at moderate heating temperature from the heater element. The electrons emitted from the cathode are accelerated by the high positive potential which is applied to the focussing and accelerating anodes. These anodes are cylindrical in form, with a small opening in the centre of each electrode, coaxial with axis of the tube. The electron beam focussed by the focussing anodes, passes through the vertical and horizontal electrostatic deflection plates and strikes the fluorescent screen. The voltages applied to these vertical and horizontal plates deflect electron beam vertically and horizontally respectively. With these two movements electron beam can be positioned anywhere on the screen. The CRT uses electrostatic method of focussing of electron beam as compared to a TV picture tube which employs electronic method of focussing. The space inside the CRT is maintained at a high vacuum to minimize collisions between gas molecules and the electron beam.

Operation of a CRT critically depends on controlling the velocity and direction of moving electrons, and in the analog oscilloscope this is done exclusively with the use of electric fields. The force exerted on an electron beam by an electric field is given by the equation

$$F = q\varepsilon \tag{6.10}$$

where, F = force on the electron in Newton, N
q = charge on the electron in Coulomb, C
ε = electric field intensity in Volt/meter, V/m

An electron is negatively charged particle whose charge is 1.602×10^{-19} coulomb, C. The force on the electron in an electric field, is thus, given by the equation

$$F = -q\varepsilon \text{ Newton} \tag{6.11}$$

where the minus (–) sign indicates that the force acts in a direction opposite to the direction of the electric field.

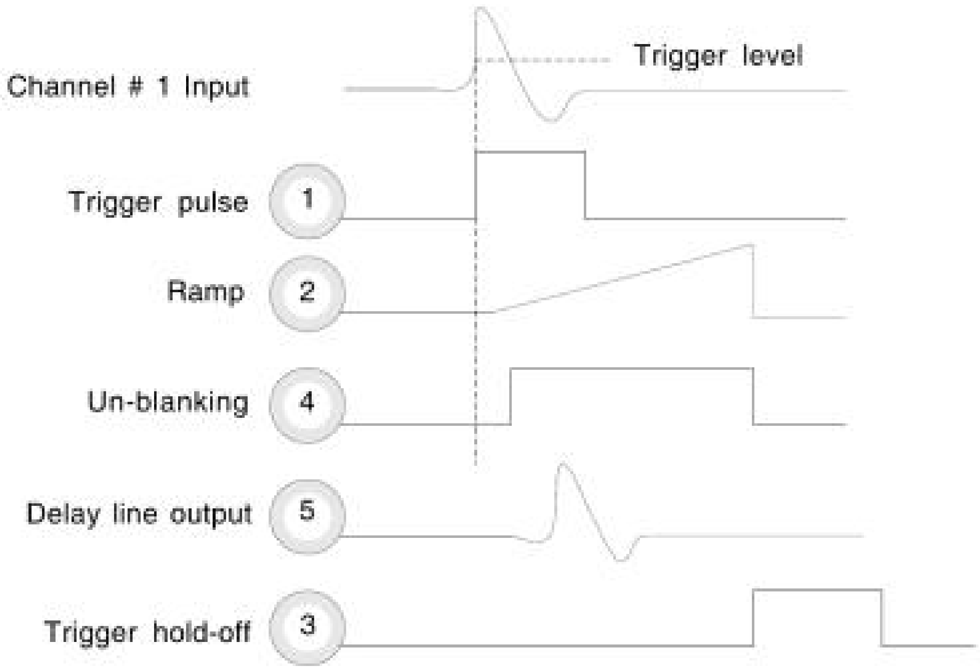

Fig. 6.20 *Waveforms from a Single Acquisition Cycle of Analog CRO*

reach full brightness. Since it is desirable to be able to view the voltage transient that caused the trigger, a means of storing the input signal during the startup delay is needed. A *delay line* is placed in the vertical path to accomplish this task. Many CRO models are equipped with an internal device for this purpose, providing enough delay time to display the trigger transient one or two divisions after the display trace starting point on the fastest time per division setting. The triggering signal at the output of the delay line is visible on the display screen while the un-blanking gate signal is at its most positive level, as shown in Fig. 6.20. A total delay time between 25 and 200 nano-seconds is required depending on the CRO model. High-bandwidth units are equipped with correspondingly fast trigger, sweep, and un-blanking gate circuits and therefore can cause a relatively short delay line. The transmission efficiency of delay lines characteristically decreases with increasing signal frequency, and this effect must be carefully compensated elsewhere in the vertical amplifier.

Two different switching modes are implemented, called *alternate* and *chopped*, but it is important to realize that both methods display a single signal that is a composite of the multiple input signals.

In the *alternate mode* of switching as shown in Fig. 6.21, the electronic switch alternatively connects the main vertical amplifier to channel # 1 and # 2. This switching takes place at the start of each new sweep. The switching rate of the electronic switch is synchronized to the sweep rate, so that the CRT spot traces channel # 1 signal on one sweep and channel # 2 signal on the next sweep. Since each vertical amplifier has a calibrated input attenuator and a vertical position control, the amplitudes of the input signals can be adjusted individually and the two images positioned separately on the screen. This mode of operation works best at relatively fast sweep speeds and signal repetition rates. At slow sweep speeds the alternating action becomes apparent, and the illusion of simultaneity is lost.

(iii) Easy signal transient capture
(iv) Stored display image
(v) Easy calibration
(vi) Printer or plotter hard copy
(vii) Automatic measurement support
(viii) Digital waveform Input/Output

Disadvantages of Digital CRO Following are the disadvantages of using digital CRO:

(i) Low throughput (waveforms/second)
(ii) High cost

6.6.6 CRO Probes

The CRO probe performs the important function of connecting the circuit under investigation to the vertical input terminals of the CRO, without loading or otherwise disturbing the test setup. To meet the requirements of the many general-purpose and special-application CROs, a variety of probes available as mentioned below are.

(i) High-impedance Passive Voltage Probe
(ii) Resistive Divider Passive Voltage Probe
(iii) Active Voltage Probe
(iv) Current Probe

High-impedance Passive Voltage Probe Passive probe is the most popular and convenient probe used for coupling the signal to be measured on the CRO. The simplest passive probe used in the CRO is known as 1 : 1 (or 1X) probe as shown in Fig. 6.24(a). It consists of a length of shielded (coaxial) cable with a probe tip at one end and a BNC connector at the other. The user's signal is modeled by the voltage V_s and the source impedance Z_s. The resistive component of the probe loading is just the CRO input resistance of 1 MΩ. Although the connection from the test point to the CRO input is a direct one, the shunting capacitance of the probe cable plays a role and must be taken into account. Therefore, the total capacitive load is the CRO input capacitance (usually between 7 and 50 pF), plus the cable capacitance. A 1-m long probe cable is approximately 50 pico-Farad (pF). This high capacitance will seriously affect the operation of many circuits and attenuate fast transients. Hence, 1X probe configuration presents a large load to high-frequency signals, and is essentially limited to low-frequency signal such as the measurement of a.c. power supply ripple.

One of the most widely used passive CRO probe is the compensated 10X (10 : 1) probe, as shown in Fig. 6.24(b). This type of probe is designed to provide signal attenuation of ten-to-one over a wide frequency range. It reduces the capacitive load on the user's circuit at the price of a 10-fold reduction in signal amplitude. It contains a parallel *RC* circuit , resistance *R* and capacitance *C* built into the probe tip combined with the cable probe capacitance and the CRO input resistance and capacitance to form a voltage divider. With this type of probe, the

by this clock with the observatory time as made available by wire transmission or radio time signals. The primary standard must be provided with very accurate means for making this comparison, since 0.01 second in one day represents slightly more than 1 part in 10,000,000 (10 million), and is somewhat greater than the error in time developed by a good primary standard in a single 24-hour period. In large laboratories, which attempt to maintain the very best in primary-standard frequencies, it has been found desirable to simultaneously operate two to four primary standards, the instantaneous frequencies of which are continuously inter-compared with each other, as well as periodically being compared against astronomical time information.

Secondary standards of frequency are very stable oscillators which have their frequency checked periodically against a primary standard. These standards are ordinarily based on carefully designed crystal oscillators. When the secondary standards need to operate only in the audio-frequency range, an electrically driven tuning fork is sometimes used. By careful design and temperature control, it is possible to obtain a constancy of frequency within a few parts in a million in this way. It is not required that the crystal be incorporated in an oscillator. Instead, the secondary standard of frequency may make use of a crystal as a fixed-frequency wavemeter having stable high-Q resonant circuit of low temperature coefficient.

The very best secondary standards of the frequency differ from primary standards only in the omission of the clock, and associated means for accurately comparing the time registered by the clock with observatory time signals. Where the utmost in frequency precision is not required of the secondary standard, it is possible to relax the design in certain respects, as, for example, less precise temperature control of the crystal, use of crystals at frequencies lying outside the optimum range, etc. In any case, a properly designed secondary standard of frequency using a crystal oscillator can ordinarily be expected to maintain its frequency constant to within a few parts in a million for long periods of time without readjustment.

The essential difference between primary and secondary standards is not necessarily in the degree of frequency stability, which is sometimes the same and sometimes quite different, but in the fact that the primary standard is directly referred to the period of the earth's rotation.

Certain classes of radio signals are very useful as frequency standards. Particularly, the National Bureau of Standards conducting a regular schedule of transmissions that include continuous operation on several carrier frequencies, and operation for a portion of each day or night on other frequencies as well. Signals from commercial radio stations, particularly broadcast stations, are often found useful as secondary frequency standards for checking heterodyne frequency meters, wavemeters, etc. Broadcast stations are particularly good sources of standard frequencies since they are in operation nearly continuously, and as a practical matter commonly maintain their frequencies to within a few parts in a million.

Although relatively stable frequency standards have been available for many years, precise frequency measurement has not been an easy measurement task. Early frequency measurement required precision standards, frequency

Fig. 6.29. As explained earlier, it works on the principle of heterodyning (mixing). The input signal to be analyzed is heterodyned (mixed) to a higher intermediate frequency (IF) by an internal local oscillator. The input signal enters the instrument through a probe connector that contains a unity-gain isolation amplifier. After appropriate attenuation, the input signal is heterodyned in the mixer stage with the signal from a local oscillator. The output of the mixer forms an intermediate frequency (IF) that is uniformly amplified by the 30 MHz IF amplifier. This amplified IF signal is then mixed again with a 30 MHz crystal oscillator signal, which results in information centred on a zero frequency. An active filter with controlled bandwidth and symmetrical slopes then passes the selected component to the meter amplifier and detector circuit. The output from the meter detector can be read off a decibel-calibrated scale or may be applied to a recording or electronic counter device.

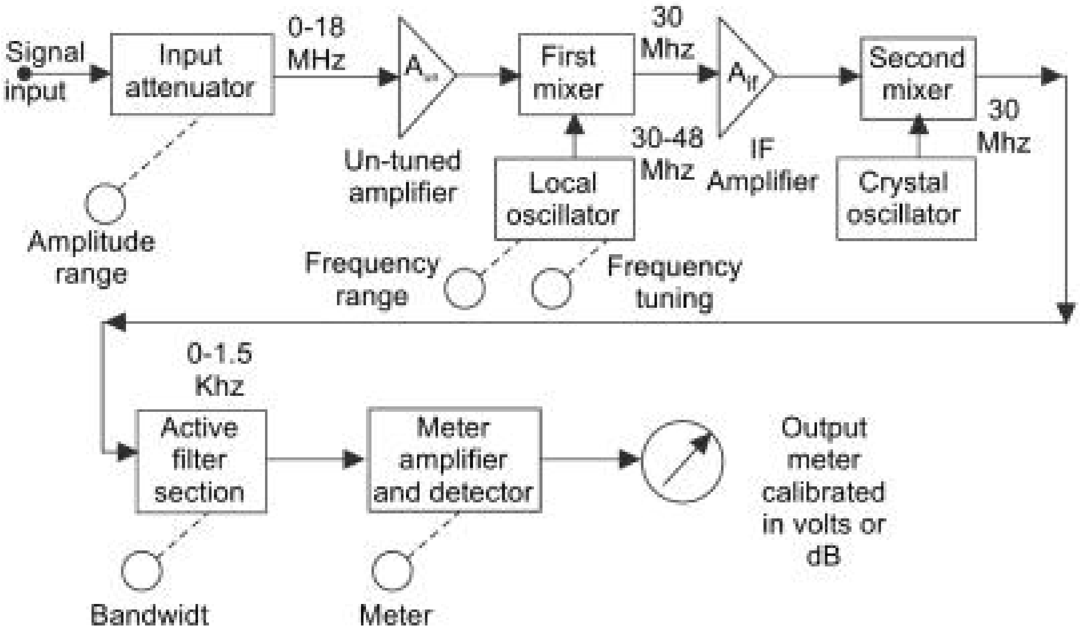

Fig. 6.29 *Block Diagram of Heterodyne Wave Analyzer*

An instrument that uses the heterodyning principle is often called a *heterodyning tuned voltmeter*. The operating range of this instrument is from 10 KHz to 18 MHz in 18 overlapping bands selected by the frequency range control of the local oscillator. The bandwidth is controlled by an active filter and can be selected at 200, 1,000 and 3,000 Hz.

Advantages

- The accuracy of the frequency indicated by a heterodyne frequency meter is ordinarily greater than the accuracy of the corresponding lumped-circuit wavemeter. This is because an oscillator generates a definite frequency for any particular setting of its resonant tank circuit, while in the case of a wavemeter using the same resonant circuit, there is an uncertainty as to exactly what setting corresponds to resonance in view of the flat-top character of the resonance curve.
- By careful design, the short-term frequency stability of a heterodyne frequency meter can be made very high, often a few parts in a million for periods of a few minutes to an hour.

component of interest. The waveform to be analyzed in terms of its separate frequency components is applied to an input attenuator that is set by the meter range switch on the front panel. A driver amplifier feeds the attenuated waveform to a high-Q active filter. The filter consists of a cascaded arrangement of *RC* resonant sections and filter amplifiers. Close-tolerance capacitors are generally used for selecting frequency ranges. Precision potentiometers are used for tuning of the filter to any desired frequency within a selected pass-band. A final amplifier stage supplies the selected signal to the meter circuit and to an untuned buffer amplifier. The buffer amplifier can be used to drive a recorder or an electronic counter. The meter is driven by an average-type detector and usually has several voltage ranges as well as a decibel scale. The bandwidth of the instrument is very narrow, typically about 1% of the selected frequency.

6.7.6 Frequency Measurement using Counters

Working Principle The basic principle for the precise determination of frequency using counters (also called frequency counters) operates on the principle of gating the input frequency into the counter for a predetermined time. For example, if an unknown frequency were gated into the counter for exactly 1 second, the number of counts allowed into the counter would be precisely the frequency of the input signal. The term 'gated' stems from the fact that an AND or an OR gate is used to allow an unknown input into the counter to be accumulated.

Construction Figure 6.32 illustrates the basic principle for the precise determination of frequency using counters. The input signal whose frequency is to be measured is converted into pulses by means of the zero-crossing detector and applied through an AND gate to a counter. To determine the frequency, it is now required to keep only the gate open for transmission for a known time interval. If, say, the gating time is 1 s, the counter will yield the frequency directly in cycles per second (hertz, Hz). The clock for timing the gate interval is an accurate crystal oscillator whose frequency is, say 1 MHz. The crystal oscillator drives a scale of 10^6 circuit, which divides the crystal frequency by a factor of 1 million. The divider output consists of a 1 Hz signal whose period is as accurately maintained as the crystal frequency. This divider output signal controls the gating time by setting a toggle FLIP-FLOP to the 1 state for 1 s.

The system is susceptible to only slight errors. One source of error results from the fact that a variation of ±1 count may be obtained, depending on the instant

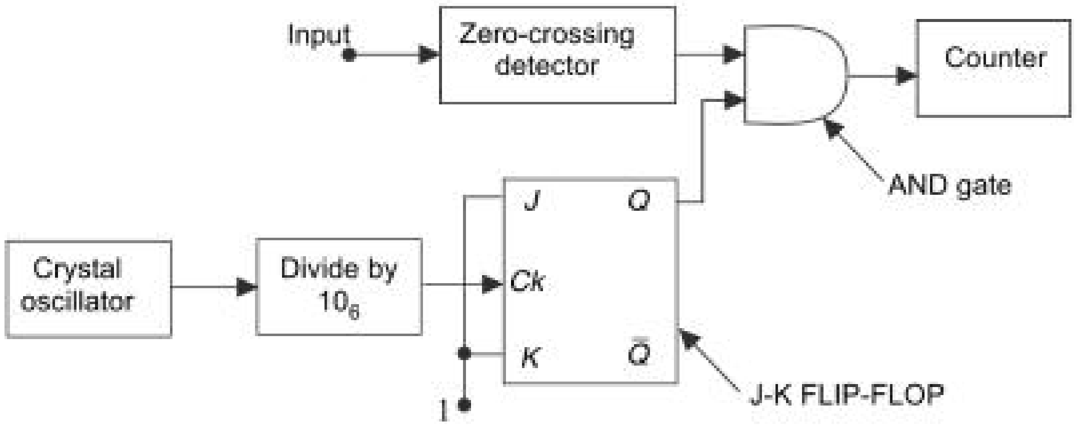

Fig. 6.32 *Frequency Counter*

amplifiers through bias adjustment to obtain equality of the two amplitudes, while simultaneously adjusting the phase shifter to produce a phase difference of 180°.

A modified version of Fig. 6.35 consists in dispensing with the phase shifter and using the voltmeter to measure the amplified output under three conditions such as (a) when both voltages are applied to their respective amplifiers, (b) when the input is removed from one amplifier (say A_{v1}), and (c) when the input is removed from another amplifier A_{v2}. Calling these respective voltages E_s, E_1, and E_2, the phase angle θ between the two waves is then given by the relation

$$E_s = \sqrt{E_1^2 + E_2^2 + 2E_1E_2\cos\theta} \tag{6.32}$$

This is the familiar equation giving the third side E_s of a triangle in terms of the other two sides E_1 and E_2, and the angle θ between E_1, and E_2. This method is suitable for all except microwave frequencies.

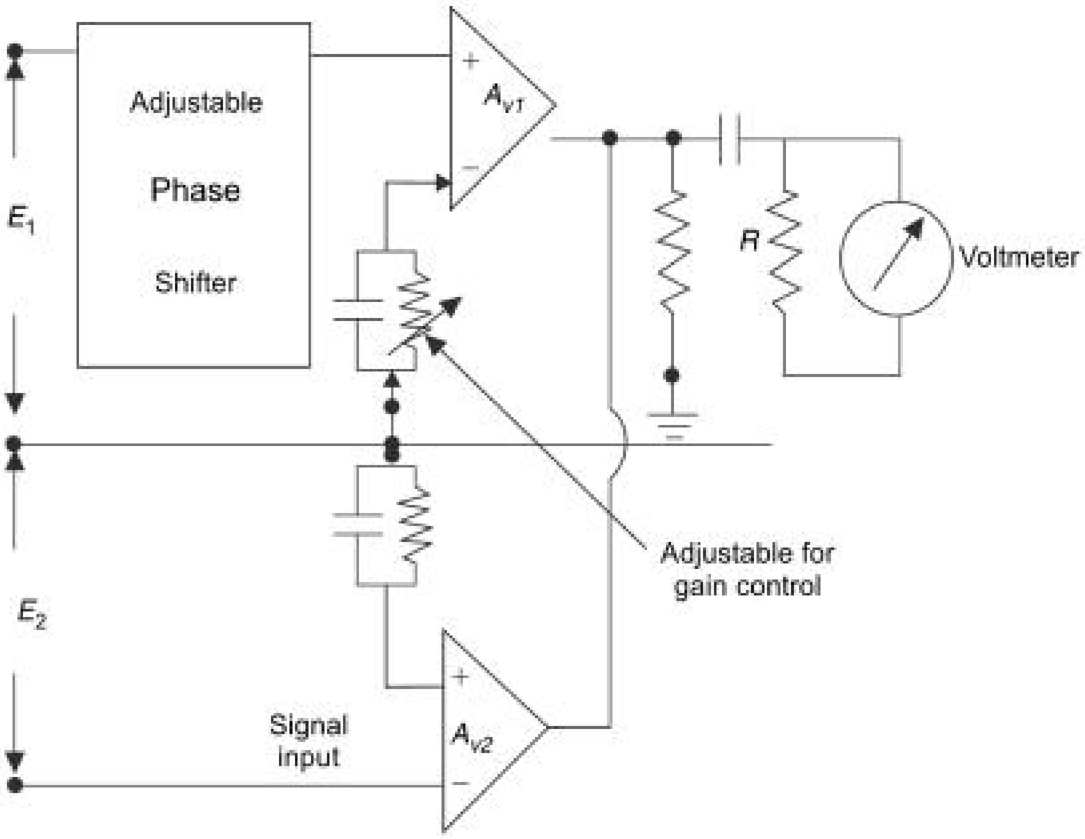

Fig. 6.35 *Voltage Addition Method of Phase Measurement*

6.8.2 Phase-Difference Meters

Construction and Working There are a number of circuits available for measuring phase difference between two waves directly on a meter. Figure 6.36 illustrates a schematic of a phase-difference meter based on the addition of square waves. The voltages whose phase difference is to be determined are applied to separate amplifier channels, which are so designed and operated that they develop square-wave outputs.

By using the same clipping level in both channels, the square waves thus produced not only have amplitudes independent of the strength of the applied voltages, but also have the same amplitude in each of the two channels. These

Working and Construction A block diagram showing various components of a standard signal generator is given in Fig. 6.38. The standard signal generator is a source of a.c. energy of accurately known characteristics. It is capable of modulating a carrier or frequency of signals such as sine- wave, square-wave, and pulse. The output signal may be either amplitude modulated (AM) or frequency modulated (FM). AM is a common feature of the standard signal generator.

A standard signal generator consists of an *RF* oscillator that uses the resonant characteristics of an inductor-capacitor (*LC*) circuit to generate a stable frequency. The oscillator consists of *LC* circuit and an amplifier with feedback network such that the total gain of the loop is exactly one, and the total phase shift around the loop is zero. The carrier frequency generated by this stable *LC* oscillator delivers a good sinusoidal waveform having no appreciable hum or noise modulation. A frequency range control and a Vernier dial setting select the frequency of oscillation. The *LC* circuit is designed to give a reasonably constant output over any one frequency range. The resonant frequency of a circuit is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{6.35}$$

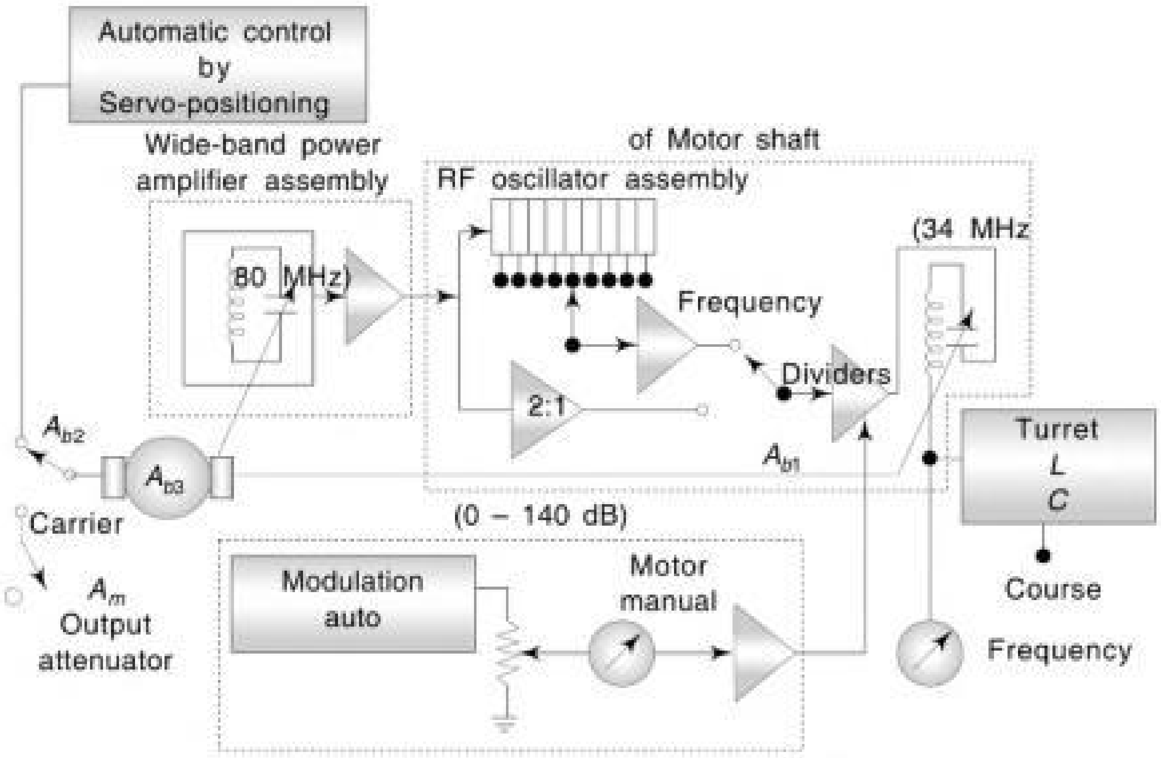

Fig. 6.38 *Block Diagram of Standard Signal Generator*

Where L = circuit inductance in henrys (H)
C = circuit capacitance in farads (F)
f = resonant frequency in hertz (Hz)

Amplitude modulation (AM) is provided from an internal, fixed-frequency sine-wave generator or from an external source. Modulation takes place in the output amplifier circuit, which delivers the modulated carrier to the output attenuator. To improve the frequency stability (which is limited by the *LC* circuit) of the basic instrument, the master controller is optimally designed for the highest frequency range, and frequency dividers are switched on to produce the lower range. The

(iii) It simulates the vibrations that aircraft and rockets are subjected to in flight, and it is commonly used in vibration and fatigue testing of aerospace components and assemblies.

(iv) Random noise is used in the test signal itself in electrical measurements.

(v) It is used in Inter-modulation (IM) distortion and cross-talk measurements in communications systems.

(vi) It is used for tests on servo amplifiers, and studies made with analog computers.

(vii) Noise of known amplitude and known spectral characteristics is used for testing various methods of signal detection and recovery in the presence of noise, as in radio, telemetry, radar, and solar systems.

6.10 FUNCTION GENERATOR

Function generator is a class of oscillator-based signal sources that provides choice of different output waveforms with adjustable frequency over a wide range. It is a versatile instrument which has number of capabilities such as continuous tuning over wide bands with max-min frequency ratios of 10 or more, fraction of Hz to MHz frequencies, flat output amplitude, and some times modulation capabilities e.g. frequency-sweeping, frequency modulation (FM) and amplitude modulation (AM). The common output waveforms produced by function generator are the sine, triangular, square, and saw-tooth waveforms.

6.10.1 Working and Construction

To realize the versatility described above, especially the wide frequency range, function generators nearly always use a basically different oscillator mechanism called threshold-decision oscillator. The threshold-decision oscillator requires following three basic elements:

(i) a circuit whose state (voltage, current, etc.) changes with time

(ii) a way to reset this circuit to an initial state

(iii) a method for deciding when to perform the reset.

Figure 6.41 (a) shows a simplified form of such an oscillator. An *RC* circuit charges from positive supply. The time-changing state of this circuit is the voltage across the capacitor. A comparator monitors this voltage and, when this reaches a reference level, momentarily closes the switch. The switch discharges the capacitor, restoring the *RC* circuit to its initial state, and the cycle restarts. Figure 6.41 (b) shows a couple of cycles of the oscillator waveform.

In order to gain some versatility, the typical function generator circuit, shown in Fig. 6.41 (c), becomes little more complex. Two current sources $i+$ and $i-$ are available to charge and discharge capacitor C. A switch, under control of a bistable flip-flop, determines which current source is connected. When $i+$ is initially connected to C, then this causes its voltage to rise linearly. When the voltage reaches the high reference, the upper comparator responds, resetting the flip-flop. This actuates the switch, connecting $i+$ to C, which then begins to discharge linearly. When the voltage of C reaches the low reference, the lower comparator responds, resetting the flip-flop and beginning new cycle.

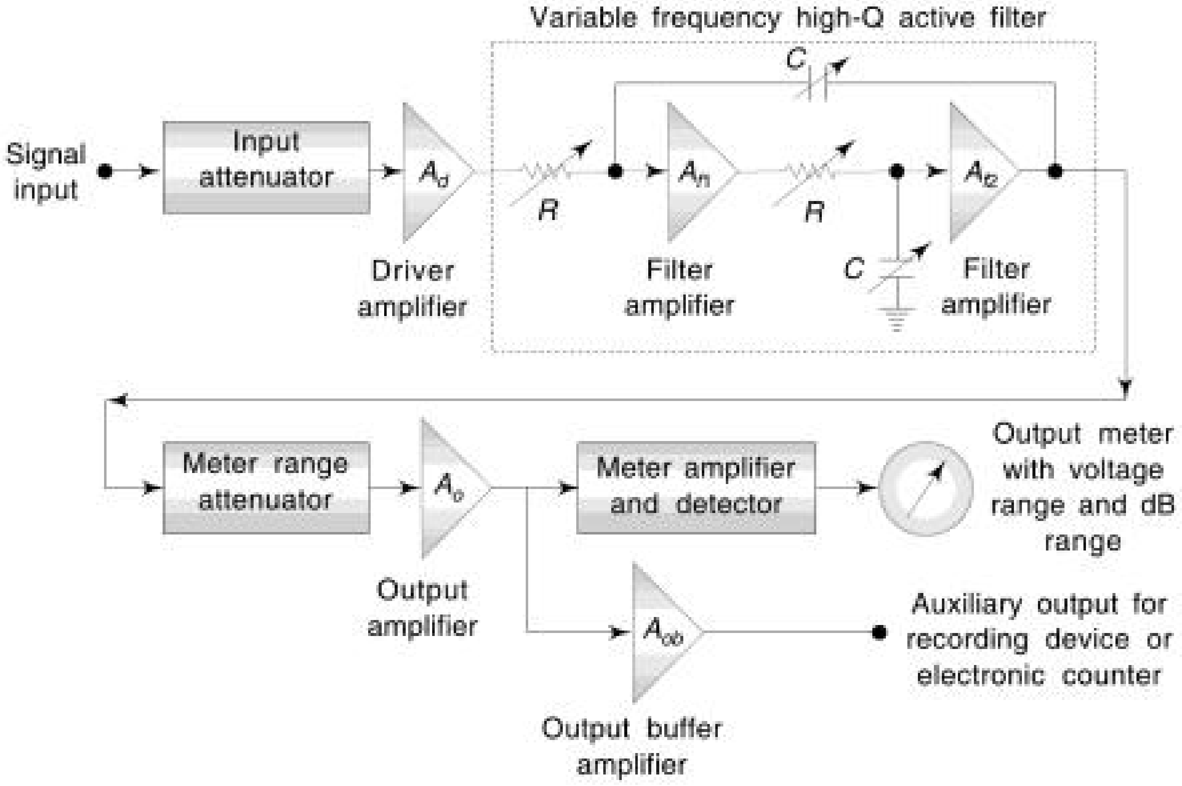

Fig. 6.44 *Functional Block Diagram of Frequency-selective Wave Analyzer*

The waveform to be analyzed in terms of its separate frequency components is applied to an input attenuator that is set by the meter range switch on the front panel. A driver amplifier feeds the attenuated waveform to a high-Q active filter. The filter consists of a cascaded arrangement of *RC* resonant sections and filter amplifiers. Close-tolerance capacitors are generally used for selecting frequency ranges. Precision potentiometers are used for tuning the filter to any desired frequency within selected pass-band. A final amplifier stage supplies the selected signal to the meter circuit and to an untuned buffer amplifier. The buffer amplifier can be used to drive a recorder or an electronic counter. The meter is driven by an average-type detector and usually has several voltage ranges as well as a decibel scale. The bandwidth of the instrument is very narrow, typically about 1% of the selected frequency.

6.11.2 Heterodyne Wave Analyzer

Heterodyne wave analyzers are used for measurement of frequencies in RF range and above (MHz ranges). This type of analyzers work on the principle of heterodyning (mixing). A block diagram of heterodyne wave analyzer is shown in Fig. 6.45.

The input signal to be analyzed is heterodyned (mixed) to a higher intermediate frequency (IF) by an internal local oscillator. The input signal enters the instrument through a probe connector that contains a unity-gain isolation amplifier. After appropriate attenuation, the input signal is heterodyned in the mixer stage with the signal from a local oscillator. The output of the mixer forms an intermediate frequency (IF) that is uniformly amplified by the 30 MHz IF amplifier. This amplified IF signal is then mixed again with a 30 MHz crystal oscillator signal, which results in information centred on a zero frequency. An active filter with

Frequency-domain instrumentation analyzes signals by using analog filtering techniques. Wave analyzers (already discussed in Section 6.10), such as the frequency-selective voltmeter, the heterodyne tuned voltmeter, the heterodyne harmonic analyzer, and the heterodyne spectrum analyzer, are examples of this type of instrumentation designed to measure the relative amplitudes of single-frequency components in a complex signal. Time-domain instrumentation analyzes signals by time sampling of the signals.

6.12.3 Spectrum Analyzer

The *spectrum analyzer* is, however, the general-purpose instrument most often used to measure distortion. With spectrum analyzer, the entire spectrum within its frequency band is analyzed even though second and third harmonic measurements are enough for many applications. Figure 6.46 shows a block diagram of the super-heterodyne spectrum analyzer.

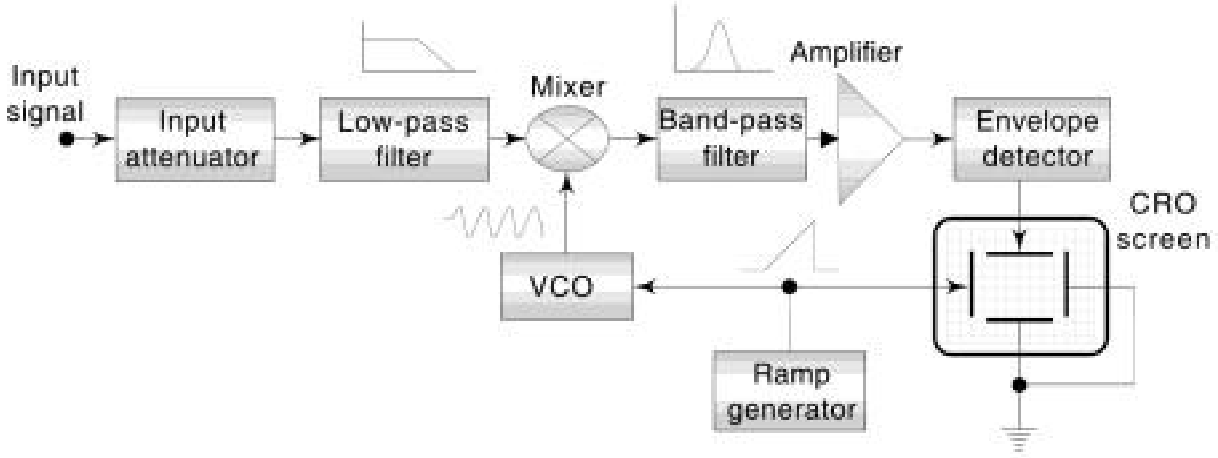

Fig. 6.46 *Block Diagram of Super-heterodyne Spectrum Analyzer*

As shown, after the input attenuator, the signal is applied to a low-pass filter the output of which is applied to a mixer. The function of the low-pass filter is to prevent the high frequencies from getting to the mixer. The bandwidth of this filter should be equal to the range of the spectrum analyzer. In the mixer, the signal is mixed with the output of a voltage-controlled oscillator (VCO). The ramp generator sweeps the VCO linearly from minimum to maximum frequency range. Because the mixer is non-linear device, its output contains the two original signals and their harmonics, the sums and differences of the original frequencies, and their harmonics. When any of the frequency components of the mixer output falls within the pass-band of the filter, a non-zero voltage is applied to the envelope detector and after amplification, to the vertical plates of CRO tube; producing a vertical deflection of the electron beam. As the ramp that commands the VCO is also applied to the horizontal plates of the CRO, the horizontal axis can be calibrated in frequency.

Super-heterodyne spectrum analyzers are not real-time instruments. They need the input signal to remain unchangeable during the sweep time, and storage CROs are necessary to display the spectrum of the input signal.

WORKED EXAMPLES

Example 1 *An electrically deflected cathode-ray tube (CRT) has a final anode voltage of 3000 volts and parallel deflecting plates 2 cm long and 5 mm apart. If the screen is 50 cm from the centre of deflecting plates, find out the deflection sensitivity of the tube and deflection factor of the CRT.*

Solution

It is given that,

The anode voltage $V_a = 3000$ volts
The length of deflecting plates $l_d = 2 \text{ cm} = 2 \times 10^{-2}$ m
Distance between parallel plates $d = 5 \text{ mm} = 5 \times 10^{-3}$ m
Distance of screen from deflecting plates $L = 50 \text{ cm} = 50 \times 10^{-2}$ m

The deflection sensitivity is given as

$$S = \frac{D}{V_d} = \frac{Ll_d}{2dV_a} \text{ meter/volt}$$

$$= \frac{50 \times 10^{-2} \times 2 \times 10^{-2}}{2 \times 5 \times 10^{-3} \times 3000}$$

or, $S = 0.333 \times 10^{-3}$ meter/volt

Similarly, the deflection factor of CRT is given as

$$G = \frac{1}{S} = \frac{2dV_a}{Ll_d} \text{ volt/meter}$$

or, $G = 3.00$ volt/meter

Example 2 *A CRT has an anode voltage of 300 volts and parallel deflecting plates 2 cm long and 5 mm apart. The screen is 20 cm from the centre of the plates. Find the input voltage required to deflect the beam through 3 cm. The input voltage is applied to the deflecting plates through amplifiers having an overall gain of 100.*

Solution

It is given that,

The anode voltage $V_a = 3000$ volts
The length of deflecting plates $l_d = 2 \text{ cm} = 2 \times 10^{-2}$ m
Distance between parallel plates $d = 5 \text{ mm} = 5 \times 10^{-3}$ m
Distance of screen from deflecting plates $L = 20 \text{ cm} = 20 \times 10^{-2}$ m
Deflection of beam $D = 3 \text{ cm} = 3 \times 10^{-2}$ m
Amplifier gain $= 100$

The deflection is given as

$$D = \frac{Ll_dV_d}{2dV_a} \text{ meters}$$

or, $$V_d = \frac{2DdV_a}{Ll_d} \text{ volts}$$

$$= \frac{2 \times 3 \times 10^{-2} \times 5 \times 10^{-3} \times 3000}{20 \times 10^{-2} \times 2 \times 10^{-2}}$$

or, $V_d = 225$ volts

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Solution

It is given that,

The coil resistance $R = 10\Omega$

The frequency at resonance $f = 5\text{ MHz} = 5 \times 10^6\text{ Hz}$

The tuning capacitor $C = 150\text{ pF} = 150 \times 10^{-12}\text{ F}$

Insertion resistance $r = 0.02\Omega$

The effective Q of the coil is given as

$$Q_e = \frac{1}{\omega CR} = \frac{1}{2\pi fCR}$$

$$= \frac{1}{2 \times \pi \times 5 \times 10^6 \times 150 \times 10^{-12} \times 10}$$

or, $Q_e = 21.21$

The indicated Q_i is given as

$$Q_i = \frac{1}{\omega C(R+r)} = \frac{1}{2\pi fC(R+r)}$$

$$= \frac{1}{2 \times \pi \times 5 \times 10^6 \times 150 \times 10^{-12} \times (10 + 0.02)}$$

or, $Q_i = 21.17$

Now, the percentage error is given as

$$\%\text{error} = \frac{Q_e - Q_i}{Q_e} \times 100$$

$$= \frac{21.21 - 21.17}{21.21} \times 100$$

or, *% error = 0.19 %*

Example 9 *Two sinusoidal waves have same frequency but different phases. The two voltage waves, with equal magnitude, are applied respectively to vertical (X-axis) and horizontal (Y-axis) plates and the pattern obtained is an ellipse. The peak Y-deflection is 5 division and its interception with positive Y-axis is at 3 division. Find the relative phase angle (a) when the major axis makes a positive slope with X-axis and (b) when the major axis makes negative slope with X-axis.*

Solution

It is given that,

The Y-axis intercept $Y_{\text{int}} = 3$ division

The peak Y-deflection $Y_{\text{peak}} = 5$ division

The sine of the phase angle between the two signals is given as

$$\sin \phi = \frac{Y_{\text{int}}}{Y_{\text{peak}}}$$

$$\phi = \sin^{-1} \frac{Y_{\text{int}}}{Y_{\text{peak}}} = \sin^{-1} \frac{3}{5}$$

(a) When slope is positive, the phase angle will be

$\phi = 37°$

(b) When slope is negative, the phase angle will be

$\phi = (180° - \text{positive slope phase angle})$

2. In a CRT, the anode to cathode voltage is 1000 volts, the parallel deflector plates are 25 mm long and spaced 5 mm. The screen is 600 mm from the centre of deflecting plates. Find beam speed and the deflection sensitivity. Charge of electron is 1.602×10^{-19} C and mass of electron is 9.109×10^{-31} kg.
3. Calculate the maximum velocity of the beam of electrons in a CRT having a cathode-anode voltage of 800 volts. Assume that the electrons leave the cathode with zero velocity, charge of electron is 1.602×10^{-19} C and mass of electron is 9.109×10^{-31} kg.
4. With the help of neat sketch and block diagrams showing essential components, explain the working of CRO and CRT.
5. Differentiate between analog and digital CRO along with their respective advantages and disadvantages.
6. An electrically deflecting CRT has plane parallel plates which are 30 mm long and 1.5 cm apart, and the distance from their centre to the screen is 20 cm. The electron beam is accelerated by a potential difference of 2500 V and is projected centrally between the plates. Calculate the deflecting voltage required to cause the beam to strike a deflecting voltage and the corresponding deflection of the screen.
7. Compute the velocity of electron beam of a CRT assuming the following data: charge of electron $= 1.602 \times 10^{-19}$ C, mass of electron $= 9.109 \times 10^{-31}$ kg, cathode to anode voltage $= 2500$ V.
8. Explain with a suitable block diagram the working of a successive-approximation type digital voltmeter.
9. Explain with simple diagram the working of a.c. and d.c. electronic voltmeters.
10. A CRT has an anode voltage of 300 V and parallel deflecting plates 1.3 cm long and 5.5 mm apart. The screen is 200 mm from the centre of plates. Find out the input voltage required to deflect the beam through 1.2 cm on the screen.
11. A cathode ray tube has an accelerating voltage of 2.5 KV and parallel deflecting plates 1.6 cm long and 0.6 cm apart. The screen is 500 mm from the centre of plates. Find the beam speed and deflection sensitivity of the tube.
12. Explain the working of a basic digital multimeter.
13. With neat sketches differentiate between average-responding, peak-responding and rms-responding a.c. electronic voltmeters.
14. Explain with diagram, implementation of alternate mode and chopped mode of switching of CRO.
15. A CRO with a sensitivity of 4 V/cm is used. An a.c. voltage is applied to the Y-input. A 15 cm long straight line is observed. Determine the a.c. voltage.
16. A coil with a resistance of 10 Ω is directly connected to the test terminal. For a 150 pF capacitance of the tuning capacitor the resonance is obtained at the oscillator frequency of 1.5 MHz. Calculate the percentage error introduced in the calculated value of Q by the 0.02 Ω insertion resistance.
17. Find the percentage error in Q measurement introduced by a 0.01 Ω insertion resistance. The tuning capacitor value and oscillator frequency at resonance are $C =$ 150 pF and $f = 5$ MHz. The resistance of the coil is 10 Ω.
18. Explain with neat sketches, the construction and working of the following along with their respective advantages and disadvantage.:
    (a) Frequency measurement (b) Phase-angle measurement

or $$\Delta R_1 = R_s\, \sigma\, (2\mu - \mu^2\, \sigma) \tag{7.7}$$

where, R_s is the resistance of the unstrained wire.

The change in resistance due to change in the length will be

$$\Delta R_2 = R_s \frac{\Delta L}{L}$$

or $$\Delta R_2 = R_s\, \sigma \tag{7.8}$$

Therefore, total change in resistance ΔR_s of wire produced by the strain will be:

$$\Delta R_s = \Delta R_1 + \Delta R_2$$

Now, putting the value of ΔR_1 and ΔR_2 from Eqs (7.7) and (7.8) respectively.

$$\Delta R_s = R_s\, \sigma\, (2\mu + \mu^2 \sigma) + R_s \sigma$$

or, $$\Delta R_s = R_s\, \sigma\, (1 + 2\mu + \mu^2 \sigma) \tag{7.9}$$

Since the strain is very small, the term containing μ^2 may be neglected.

$\therefore$ $$\Delta R_s = R_s\, \sigma\, (1 + 2\mu) \tag{7.10}$$

Gauge Factor The gauge factor of the strain gauge is defined as the unit change in resistance per unit change in length.

$\therefore$ $$G = \frac{\Delta R_s / R_s}{\Delta L / L} \tag{7.11}$$

or $$G = \frac{\Delta R_s / R_s}{}$$

Now putting the value of ΔR_s from Eq. (7.10)

$$G = \frac{R_s \sigma\, (1 + 2m)}{R_s \sigma}$$

or $$G = (1 + 2\mu) \tag{7.12}$$

where G = Gauge factor

Poisson's ratio for most metals lies in the range 0.25 to 0.35, and accordingly the gauge factor in the range 1.5 to 1.7.

Types Basically, there are two types of strain gauges:

(i) Bonded strain gauge

(ii) Unbonded strain gauge

Bonded Strain Gauge In bonded strain gauges, a grid of fine wire is cemented to a thin paper sheet or very thin bakelite sheet, and covered with a protective sheet of paper or thin bakelite. The paper sheet is bonded with an adhesive material to the structure under study. The most useful form of bonded strain gauge is shown in Fig. 7.1(a).

When the surface to which the strain gauge is bonded is disturbed because of an applied force (or load), the strain gauge is also strained. The resistance of the wire changes on account of change in length and diameter of the wire.

The size of the grid varies with the application. They can be as small as 3 mm × 3 mm square. Usually they are larger, but seldom more than 2.5 cm long and 1.25 cm wide.

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(iv) Temperature affects the performance of the transducer. Temperature also causes phase shifting effects which may be minimized by using a capacitor across one of the secondary windings.

7.2.3 Capacitive Transducer

Operating principle of capacitive transducer is based upon the familiar capacitance equation of a parallel plate capacitor, which is given by:

$$C = \frac{\varepsilon_0 \, \varepsilon_r \, A}{d} \text{ farads} \tag{7.13}$$

where C = capacitance, in farads
A = area of each plate, in m^2
D = distance between two plates, in m
$\varepsilon_0 = 8.854 \times 10^{-12}$ farad/m^2
ε_r = dielectric constant, known as relative permittivity.

Since the capacitance of a parallel-plate capacitor is inversely proportional to the spacing (or distance) '*d*' between the two plates, any variation in '*d*' causes a corresponding variation in the capacitance. This principle is applied in the capacitive transducer for the measurement of displacement (Fig. 7.3).

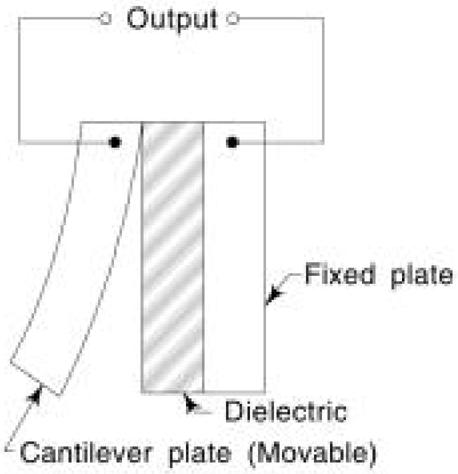


Fig. 7.3 *Capacitive Transducer*

Construction and Working It consists of two plates, one fixed and the other free to move as the displacement is applied on it. The movable plate works as a cantilever plate which is spring controlled. As the displacement is applied to the cantilever plate, it moves towards the fixed plate, decreasing the distance between the two plates. Due to this decrease in distance, the capacitance of a capacitor increases. The air between the two plates works as a dielectric medium. The capacitance of an air dielectric capacitor does not vary linearly with change in distance between the plates and therefore this arrangement is fundamentally non-linear. However, linearity can the closely approximated by keeping the change in the distance small or by having a medium of high dielectric constant in the space between the two plates. This type of capacitive transducer may be used to measure displacements of the order of 1×10^{-7} mm. Linearity can be achieved over a range of 0.04 mm. Sensitivity can be about 0.4 micro-farad/0.001 mm.

Advantages The advantages of capacitive transducers are:

(i) Very little force is required to operate them and hence they are very useful in small systems.

(ii) They are extremely sensitive.

(iii) They have a good frequency response and can measure both static and dynamic changes.

(iv) A resolution of $2.5´ \, 10^{-3}$ mm may be obtained with these transducers.

(ii) They respond slowly to sudden load changes and therefore are not generally used for test work.

7.3.3 Electric Force Transducers

Force measurement is also done by electric means in which the force is first converted into a displacement at an elastic element and then the displacement is measured. Different types of electrical force transducers are discussed below.

Proving Ring The proving ring utilises the principle of a linearvariable differential transformer (LVDT) which senses the displacement caused by the force resulting in a proportional voltage.

Construction and Working A proving ring is shown in Fig. 7.6. It consists of a circular ring of precisely known diameter, provided with projection lugs for compressive loading. An LVDT is attached with the integral internal bosses *C* and *D* for sensing the displacement caused by the application of force.

When the forces are applied to the ring through the integral external bosses *A* and *B*, the ring changes its diameter due to the compression or tension effects which is known as "ring deflection". The resulting deflection of the ring is measured by LVDT which converts the ring deflection (or displacement) into a voltage signal directly proportional to the displacement. An external amplifier may be connected to provide d.c. voltage or current to drive the conventional recorders or indicators to indicate the measured value of force. In place of LVDT, any other displacement sensing transducers can be used.

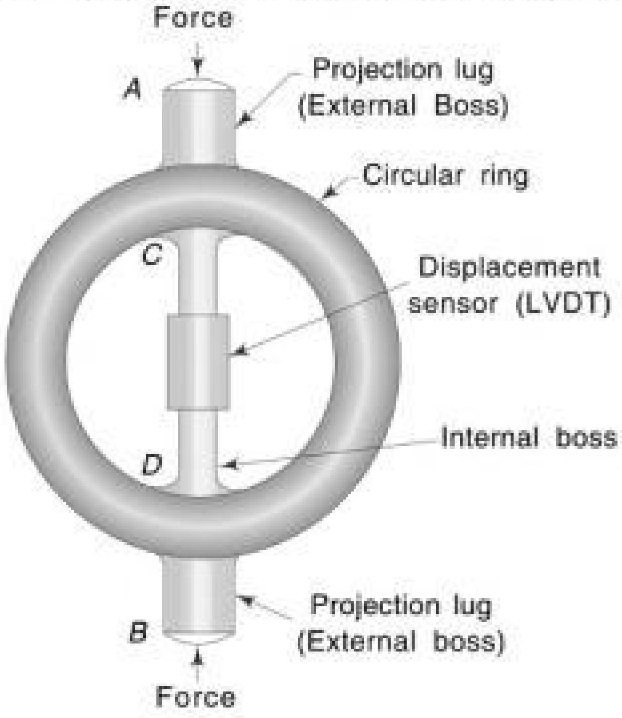


Fig. 7.6 *Proving Ring*

With this type of instrument, forces in the range of 0.0045 to 45,000 kg (0.01 to 100,000 lb) can be measured with a rated output range of 5 to 200 mV per volt of excitation. Its linearity range is from 0.1 to 0.5%, and repeatability is 0.05%.

Advantages Following are the advantages of proving rings:

(i) These instruments furnish relatively high output signal levels.

(ii) They give high accuracies.

(iii) They cover a broad range of measuring capacities.

Strain Gauge Load Cell The strain gauge load cell is an electro-mechanical transducer which translates changes in force (or weight) into changes in voltage. The change in voltage can be calibrated directly in terms of the force (or load) applied to the cell.

Construction and Working The in-line rotating torque sensor consists of a metal shaft with bonded strain gauges electricallly connected in the form of a wheatstone bridge. Figure 7.9(a) illustrates the stresses acting on a rotating shaft subject to torsion. The strain gauges are kept on the shaft at precisely 45° to the shaft axis to sense compressive and tensile deformation due to torsion. The strain gauges 1 and 3 must be diametrically opposite as must strain gauges 2 and 4. In one direction, at 45° angle to the axis, pure tensile stress exists, whereas 45° in the other direction pure compressive stress is extant. The rotor shaft is elastic and will deflect minutely under the imposed stresses. The output of the wheatstone bridge is in proportion to torsion and hence to the applied torque on the shaft. Bridge power and output voltage may be connected to the sensor through slip rings and brushes, but this type of pickoff is limited to rotational speed in the order of 30 m/s at the brush surfaces. Also, with this type of system, the measurement is affected due to the contact resistances, contact friction, and heating effect.

A sensor with non-contacting power supply and signal pickoff is shown in Fig. 7.9(b), in which the disadvantages of the slip ring are avoided. The bridge power and output signals are transmitted between the rotating and stationary members through transformers T_1 and T_2. The bridge power is a constant-amplitude, high-frequency sine wave, and the output is a sine wave of the power frequency whose amplitude is a function of torque. The power supply system consists of an oscillator to generate the carrier frequency. The output

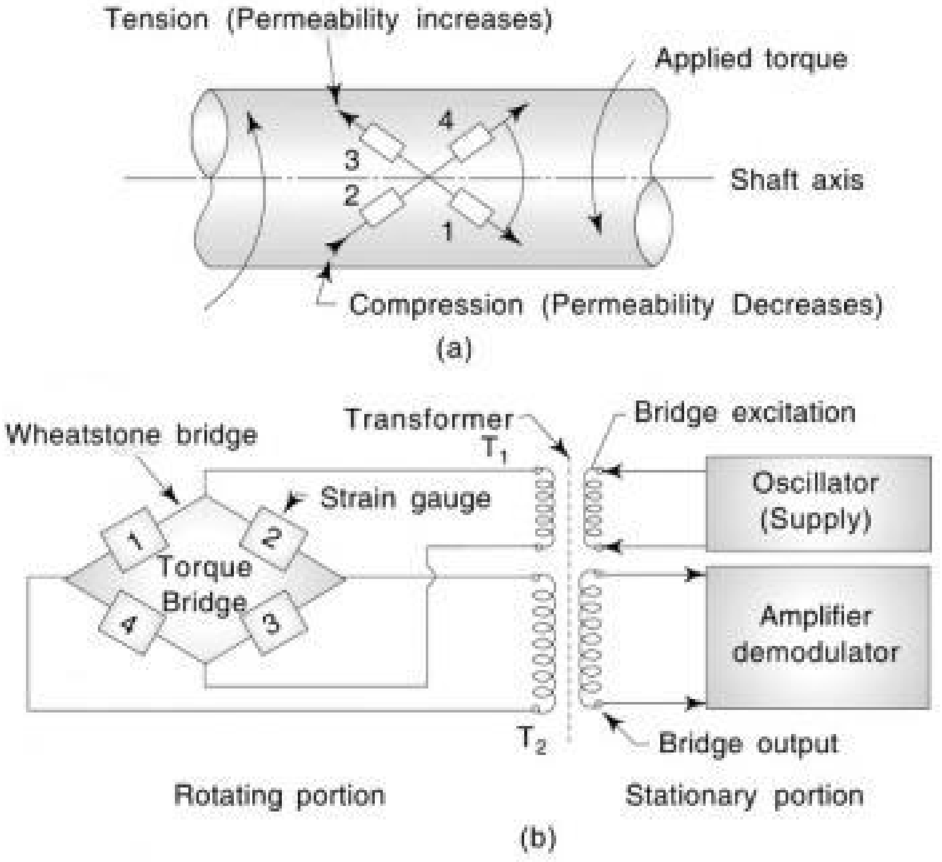


Fig. 7.9 *In-line rotational torque measurement using strain gauge,*
(a) Tension-compression stresses on surface of a circular shaft
(b) Wheatstone bridge

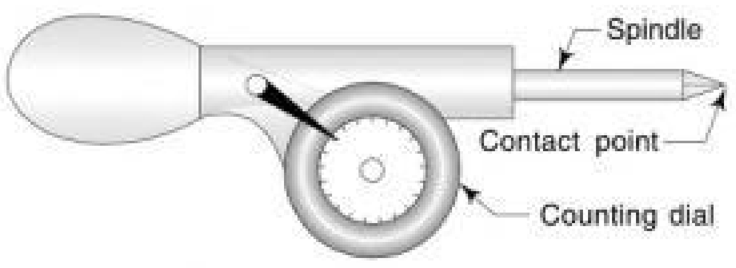


Fig. 7.12 *Revolution Counter*

For measuring the speed, a revolution counter is manually held, and the worm gear attached to the spindle is rotated by pressing the contact point of the spindle against the rotating shaft whose rotational speed is to be measured. The worm gear moves a calibrated dial through the spur gear, indicating total revolutions of the spindle which is in contact with the shaft. The stopwatch is started and stopped simultaneously with the counter and thus the average speed is calculated.

The manual operation of starting and stopping the stopwatch simultaneously with the counter is practically not always feasible. Therefore, a tachoscope is provided in some of the models in which a counter is combined with a timepiece. In this case, both the stopwatch and counter start simultaneously when the contact point is pressed against the rotating shaft, and both are stopped when the point is removed.

In some of the other arrangements, an automatic timer is used in which a rachet arrangement on a measuring wheel frees the wheel for a definite period of time, and the pointer on the wheel indicates the speed directly, in rpm, on a calibrated dial.

7.5.2 Resonance Tachometer

The resonance tachometer employs a vibrating-reed type speed indicator which senses the repeated machine-vibrations frequency due to reciprocating movement of the pistons, for the measurement of engine speed.

Construction and Working A resonance tachometer consists of a series of consecutively tuned steel reeds of varied length, as shown in Fig. 7.13. One side of each reed is fixed to a base which is kept in contact with a moving part of the machine, while the other sides of the reeds are attached to a part at the boottom of which a calibrated scale is attached that gives reading directly in rpm.

When speed of the engine or machine (whose speed is to be measured) increases, the vibration of the base of the machine assembly also increases.

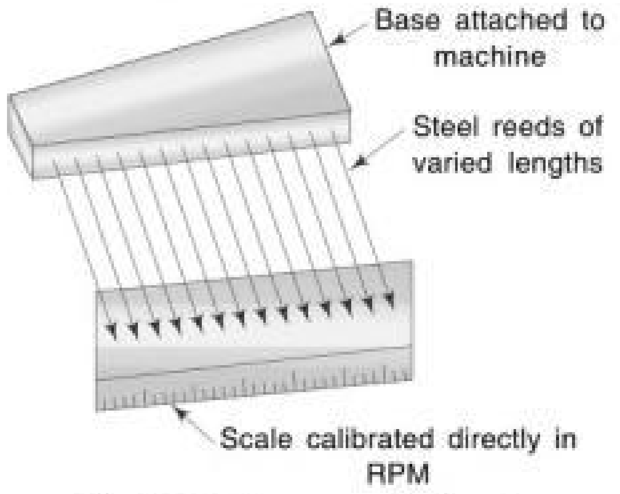


Fig. 7.13 *Resonance Tachometer*

the gear is passed. Thus, a voltage is generated in the coil which is proportional to the rate of change of flux in the pole piece and also proportional to the speed at which the ferromagnetic gear makes the flux build up or collapse. The output voltage waveform varies depending upon the teeth shape of the gear, thickness, and spacing, and the output voltage amplitude is proportional to the clearance between the pickup tip and the surface of the gear. The frequency of the voltage build-ups (and collapses) is linearly proportional to rpm. The output frequency of the magnetic pickup is given as,

$$f = \frac{\text{rpm} \times \text{No. of gear teeth}}{60} \tag{7.16}$$

where, f = frequency, in Hz

Magnetic pickups provide an accurate indication or record of equipment speed (rpm) and may be used on any type of surface, such as vibrating, rotating or moving surface. They may be operated under conditions when oil, water or non-corrosive liquids are present. They are available in ranges from 0 to 25 rpm to 0 to 72,000 rpm, with calibrated accuracy of ± 1/2% full-scale, and reproducibility of 0.2% full-scale.

SELF-CHECK QUIZ

A. Tick (✓) the appropriate answer:-

1. LVDT is used for the measurement of
   - (a) displacement (b) motion
   - (c) force (d) pressure
2. Revolution counter is used for the measurement of
   - (a) displacement (b) speed
   - (c) acceleration (d) none of these
3. Magnetic pick-up sensors produce
   - (a) pulses from a rotating shaft with mechanical contact
   - (d) pulses from a rotating shaft without any mechanical contact
   - (c) an analog signal in the form of a continuous drag
   - (d) none of these
4. In the in-line rotating torque sensor, the strain gauges are kept on the shaft precisely at
   - (a) 45° to the shaft axis (b) 60° to the shaft axis
   - (c) 30° to the shaft axis (d) 90° to the shaft axis
5. Pneumatic force meter has an accuracy of
   - (a) ± 1/2% (b) ± 3/4%
   - (c) ± 1/4% (d) none of these

B. Fill-up the blanks:-

1. The resistance of a wire is directly proportional to ______ and ______.
2. Gauge factor of the strain gauge is defined as the unit change in ______ per unit change in ______ .

Other contact-type thickness meters are available which work on electrical methods for the measurement of thickness of a stock or a product, e.g.

(i) Inductive type

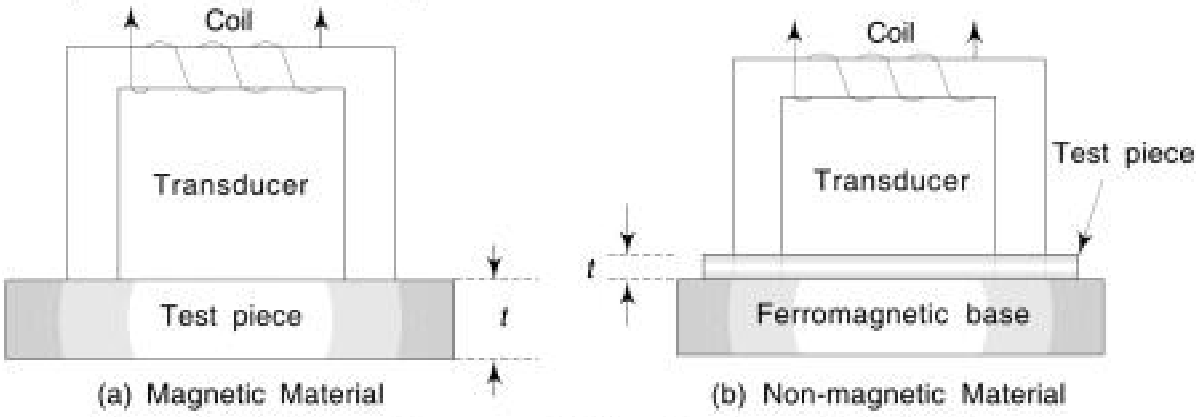
(ii) Capacitive type

(iii) Ultrasonic Vibration type

Inductive Methods of Thickness Measurement

Construction and Working Inductive methods of thickness measurement use reluctance variation transducers and eddy current transducers. Figure8.2(a) illustrates the measurement of thickness of a magnetic material using a reluctance variation transducer. The transducer consists of a U-shaped magnetic core over which a coil is wound. The stock or a test piece, whose thickness is to be measured, completes the magnetic circuit. Inductance of the coil depends upon the reluctance of the magnetic circuit, which in turn depends upon the thickness of the test piece. Therefore, the inductance of the coil provides a measurement of the thickness of the magnetic test piece and this can be calibrated into thickness on scale reading.

The reluctance variation transducer as shown in Fig. 8.2(b) can also measure the thickness of non-magnetic materials. The non-magnetic material test piece is placed on a ferromagnetic base. The ferromagnetic base is thick such that the reluctance of the magnetic circuit is determined by the distance between the ends of the U-core and the base plate, i.e. by the thickness of the test piece. An increase in thickness of the test piece causes an increase in reluctance and a decrease in inductance of the magnetic circuit. Therefore, by measuring inductance, the thickness of the product or stock can be known.



(a) Magnetic Material (b) Non-magnetic Material

Fig. 8.2 *Thickness Measurement Using Reluctance Variation Transducer*

The thickness measurement of conducting and non-conducting materials using eddy current transducers is shown in Fig. 8.3. The eddy current transducer used for thickness measurement of non-magnetic but conducting material consists of a coil wound on an insulated core, as shown in Fig. 8.3(a). The coil is excited by an alternating current supply. The alternating field produces eddy currents in the test piece or metal backing. The magnetic field produced by eddy current opposes the magnetic field of the coil and, therefore, the inductance of the coil is reduced. The higher the thickness of the test piece, higher will be the eddy currents and lower would be the inductance of the coil.

indicated by a sudden sharp rise in power absorbed from the transducer. Thickness of test piece is calculated as per Eq. (8.4).

Advantages

(i) Under static conditions, thickness from 2.5 mm > 35 cm may be measured with great accuracy.

(ii) These gauges can measure wall thickness to within 1% error.

Disadvantages

(i) This device is not suitable for dynamic reading of moving material because accurate dimensioning requires intimate contact between the generator crystal and the surface of the material.

(ii) Ultrasonic transducers are listed under contact-type device because they require a continuous sonic path between the part (test piece) being measured and the transducer.

Application These gauges are extensively used for wall thickness measurement of metal, plastic, or ceramic equipment.

8.2.2 Non-contact Type Thickness Measurement

In non-contact type thickness gauge, the measurement is performed without any physical contact of the instrument (transducer) and the test piece. In these types of measurements, certain properties of materials are used to indirectly indicate the thickness of sheets or films of those materials. Most commonly used non-contact type thickness gauges are

(i) Capacitance type

(ii) Radiation type

(iii) Laser based

Capacitance Type Non-contact Thickness Gauge

Construction and Working The capacitance gauges are used for thickness measurement of insulating films. As explained in Eq. (8.3), the capacitance varies directly in relation to the thickness of the dielectric material between the two parallel capacitor plates. The test piece whose thickness is required to be measured, works as a dielectric material. Figure 8.6 illustrates the working of a capacitance type thickness gauge for measuring thickness of insulating materials.

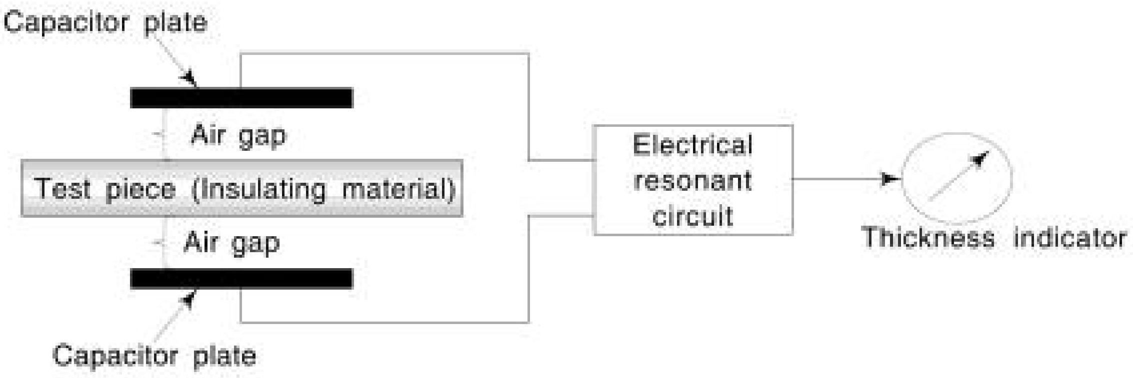
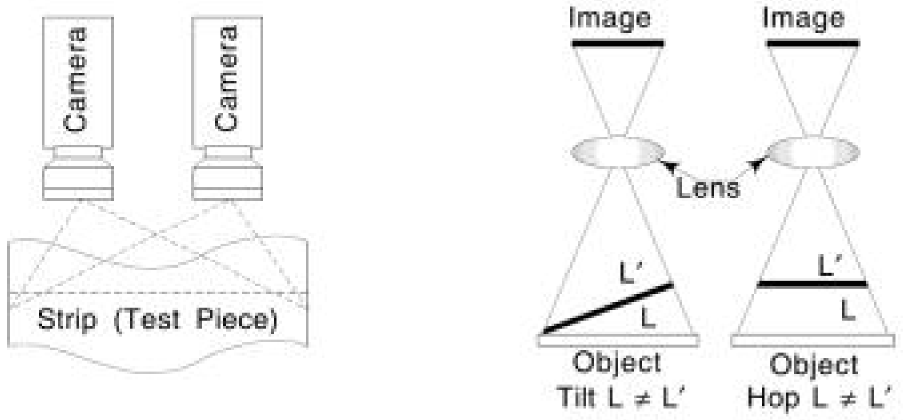


Fig. 8.6 *Capacitance Thickness Gauge*



(a) Stereoscopic Vision Principle (b) Hop/Tilt Measurement

Fig. 8.14 *Camera-based Width Measurement System*

In the stereoscopic configuration, each of the cameras has a view of the complete strip. The field of view can be adjusted to measure wide range of widths. The resolution of the camera is about 1 mm. Higher resolution can be achieved for the vertical camera configuration.

Data from both the line scan cameras are captured at the same time. These data are processed in a computer. Sophisticated edge detection algorithm is applied to detect the edges of the strip. Various other correction logics are applied like lens aberration correction, camera angle compensation, etc. To improve the measuring accuracy, inter-pixel interpolation technique is applied.

8.4.2 Advantages

(i) This instrument has high accuracy.

(ii) Lens error compensation and temperature compensation are provided.

(iii) This instrument helps in on-line width control.

8.4.3 Applications

(i) Width measurement can be done of both cold and hot rolled steel strips and slabs in a steel industry.

(ii) Width profile of the strip can also be measured along the length of strip for control.

8.5 LASER DIAMETER GAUGE

8.5.1 Working and Construction

Laser diameter gauge is a laser-based system to accurately measure the diameter of any type of opaque rod or rounds. The laser beam emitted from the laser diode in the transmitter is converged into a parallel beam by the projecting lens unit. The laser beam is then directed through the slit on the receiver and focused on the light-receiving element. As the target moves through the parallel laser beam, the change in the size of the shadow is translated into the change in received light quantity (voltage). The resulting voltage is calibrated to read corresponding diameter of the target (test piece). Figure 8.15 illustrates the working of a laser diameter gauge.

9

Density, Viscosity and pH Measurements

9.1 INTRODUCTION

Physical properties are those properties of a substance which do not change irrespective of the size of the sample that is examined. From the instrument point of view, the physical properties of materials are often involved in the design of instrument components. They are also an important factor in calibration of some meters and in the sizing of devices such as flowmeters, control valves, and safety valves. In this chapter, measurement of some of the important physical properties is explained.

9.2 DENSITY MEASUREMENT

Density is the most fundamental of all the physical properties. It applies to substance in any of the three states namely solid, liquid, or gas. By measuring the density of a process stream, one can determine its concentration, composition or, in the case of fuels, its calorific value. Density measurement is also necessary to convert volumetric flow measurements into mass flow information. Most substances have their own peculiar value of density; hence it is often possible to identify a substance if its density can be measured.

Density is defined as the mass per unit volume of a substance under fixed conditions. It is usually denoted by the Greek letter rho (ρ) and is given by

$$\rho = \frac{m}{V} \text{ kg/m}^3 \tag{9.1}$$

where, ρ = density of a substance
m = mass of a substance in kg
V = volume of the substance in m^3

The most common units of density are kilogram/m^3 (kg/m^3) or gram/liter (g/l) or gram/milliliter (g/ml).

Since the volume of most substances changes with temperature, the density depends on the temperature and pressure of a substance. This dependence is much greater in gases. Increasing the temperature of a sample of a substance generally increases its volume and therefore decreases its density.

The volumetric effect of temperature on the density of liquids or solids may be expressed as

$$V = V_0 (1 + \beta \Delta t) \tag{9.12}$$

where β = the coefficient of expansion of solids or liquids which is constant with the temperature units used

V = volume of solid or liquid

V_0 = volume of solid or liquid at 0° temperature.

As the mass is same before and after temperature rise, the change in density is inversely proportional to the change in volume and can be expressed as

$$\frac{\rho}{\rho_0} = \frac{V}{V_0} \tag{9.13}$$

where $\frac{\rho}{\rho_0}$ = change in density

$\frac{V}{V_0}$ = change in volume

If the solid samples have a regular shape and are uniform, the determination of its density is a simple task. Once the volume and mass of the solid are known, the density may be found by using the basic ratio; density = mass/volume (kg/mg^3). In order to avoid errors, the weights and volumes must be determined by using accurate instruments.

However, in many applications, solids have different constituents and are made up from the mixture of different materials. The volumetric ratios of constituents may also change.

A common method of determining the density of irregular and non-uniform samples is the hydrostatic weighing. In some cases, dynamic methods are employed, such as radioactive absorption and ultrasonic methods.

Powdered solids occlude air between or inside individual particles, giving rise to apparent, bulk, tap, effective, and true densities. The apparent densities include the air lodged in the cavities or pores, and the density is determined without filling up the pores. The numerical value of the density depends on the amount of compacting employed (tap density) which can be achieved by moderate mech anical means and also embedded foreign particles (effective density). For true density, it is necessary to dislodge the air by means of suitable liquids or gases. Special pyrometers are developed for this purpose.

9.2.4 Liquid Density Measurement

Overall density of fluid is the ratio of total mass to total volume. *Point density* is the ratio of molecular mass in a volume element centered at a point to the element's volume(s) the volume being much smaller than the total volume. As in the case of solids, the densities of liquids are affected by temperature and pressure. Most liquids are incompressible, therefore, pressure effects may be neglected. Nevertheless, in determination of liquid densities, the effects of temperatures must carefully be monitored as indicated in Eqs (9.12) and (9.13).

and is defined as the ratio between the actual specific weight and the theoretical based on the perfect gas law. If the gas pressure, temperature, specific gravity, and flowing density are measured, then the super-compressibility factor is calculated as follows:

$$Z = \frac{P \times \mathrm{SG}}{\rho \times T \times R_{air}} \tag{9.29}$$

where, Z = super-compressibility factor (dimensionless)
P = operating pressure (lbf/in.^{2})
SG = specific gravity (dimensionless)
ρ = flowing density (lbm/ft^3)
T = absolute temperature (°R or °K)
R_{air} = gas constant for air 53.3 (ft-lbf/lbm °R)

9.2.6 Magnetic Methods of Density Measurement

Magnetic method of density measurement (also called magnetic densitometer) is used for both liquids and gases. It allows the determination of effects of pressures and temperatures down to cryoscopic range.

Construction and Working Figure 9.1 shows a block diagram of a magnetic densitometer illustrating the various elements. It consists of a small ferromagnetic cylinder, encased in a glass jacket. The jacket and ferromagnetic material combination constitutes a buoy or float. Therefore, float is suspended electromagnetically, totally immersed in the process fluid whose density is required to be measured. The cylinder is held at a precise height within the medium by means of solenoid which is controlled by a servo system integrated with a

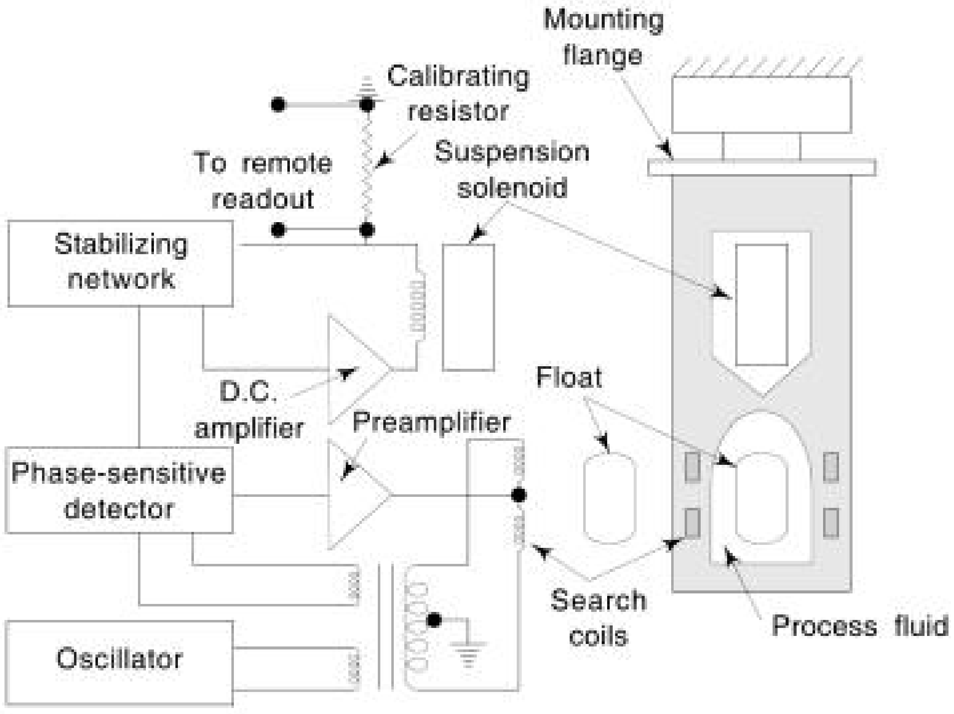


Fig. 9.1 *Magnetic Densitometer*

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As shown in the Fig. 9.2, the process fluid flows continuously through a 9.5 mm (½ inch) diameter U-tube section which is welded at the end structure. The tube length is approximately 20 times greater than the tube diameter. The process fluid density affects the total mass of the U-tube assembly. A pulsating current in the drive coil brings the tube into mechanical vibration. An increase in process density increases the effective mass of the tube and, therefore, decreases the corresponding vibration amplitude.

As shown in Fig. 9.2, the tube containing the process fluid is vibrated at resonant frequency by electromagnetic or piezoelectric vibrators. The tube and the driving mechanisms are constrained by this to vibrate on a single plane. The resonant frequency is a function of the density of the fluid moving inside the tube. The tube is isolated from the fixtures by carefully designed bellows.

One major design problem with the vibrating tube method is the conflict to limit the vibrating element to a finite length, and also accuracy of fixing the nodes. The twin tubes, on the other hand, offer very small blockage, and they can be easily inspected and cleaned. Their compact sizes are another distinct advantage. In some densitometers, the twin tubes are designed to achieve a good dynamic balance with the two tubes vibrating in anti-phase. Their nodes are fixed at the ends, demonstrating maximum sensitivity to installation defects, clamping, and mass loadings.

The main design problems of the vibrating tube sensors cause in minimizing the influence of end padding and overcoming the effects of pressure and temperature. Bellows are used at either ends of the sensor tubes to isolate the sensors from external vibrations. Bellows also minimize the end loadings due to differential expansion and installation stresses.

The fluid runs through the tubes, therefore, it does not require pressure balance. Nevertheless, in some applications, the pressure stresses the tubes, resulting in stiffness changes. Some manufacturers modify the tubes to minimize the pressure effects. In these cases, corrections are necessary only when high accuracy is needed. The changes in the Young's modulus with temperature may be reduced to almost zero by using Ni-span-C material whenever corrosive properties of fluids permit. Usually, manufacturers provide pressure and temperature correction coefficients for their products.

Each vibration densitometer is calibrated against other methods as a transfer of standards. Often, the buoyancy method is used for calibration purposes. The temperature and pressure coefficients are normally found by exercising the transducer over a range of temperatures and pressures on some liquid of well known properties. Prior to calibration, the vibration tube densitometers are subjected through a programmed burn-in cycle for stabilization against temperatures and pressures.

Advantages The design pressures and temperatures are not limited by flexible connectors and ambient temperature, process pressure, sample flow rate, or viscosity variations have practically no effect on the measurement.

k = spring constant, pound-force/inch or lb/s^2 or N/m or kg/s^2
m = mass of the system, lb or kg

For the coriolis densitometer, the mass of the system is the combined mass of the fluid and the flow tube, and can be expressed by the following relationship:

$$m = \rho_f A_f l_t + \rho_t A_t l_t \tag{9.32}$$

where, m = mass of the system, lb or kg
ρ_f = fluid density, lb/in^3. or g/cc
ρ_t = tube material density, lb/in^3. or g/cc
A_f = tube internal area, in^2. or cm^2.
A_t = tube cross-sectional area, in^2. or cm^2
l_t = tube length, in^2. or cm

The spring constant k, from Eq. (9.31), is a function of geometry and material properties and is determined from the equation given as

$$k = \frac{MEI}{l_t^3} \tag{9.33}$$

where, M = modal constant
E = modulus of elasticity, pound-force/in^2 or kPa
I = moment of inertia, in^4 or cm^4

The natural frequency ω_n, from Eq. (9.31), can also be expressed by the following equivalent relationship:

$$\omega_n = 2\pi f = \frac{2\pi}{T} \tag{9.34}$$

where, f = oscillation frequency, cycles/s
T = tube period, sec

Substituting Eqs (9.32), (9.33), and (9.34) into Eq. 9.31 and solving for fluid density ρ_f, gives the following relationship:

$$\rho_f = \left(\frac{MEI}{4\pi^2 l_t^4 A_f}\right) T^2 - \frac{\rho_t A_t}{A_f} \tag{9.35}$$

The variables that depend upon the tube geometry and material properties can be determined to obtain calibration constants, such that

$$K_1 = \frac{(MI)}{(4\pi^2 l_t^4 A_f)}$$

and $$K_2 = \frac{(\rho_t A_t)}{(A_f)}$$

A correction factor C_r is used to compensate for changes in the material modulus of elasticity E with temperature. Equation (9.35) can then be rewritten as

$$\rho_f = K_1\, C_r\, T^2 - K_2 \tag{9.36}$$

Values for the calibration constants are determined by measuring the tube period at two known fluid densities. With the two fluid densities and their

methods employed for it. The most common commercial meters use a force balance system. The connectors are stainless steel bellows. In some cases, rubber or other materials are used, depending on the process fluid characteristics and the accuracy required. There are temperature, flow rate, and pressure limitations due to bellows, and the structure of the system may lead to a reading offset. The meter must securely be mounted on a horizontal plane for best accuracy.

Advantages

(i) Hydrostatic densitometers are rugged.
(ii) They give accurate results.
(iii) They are used for the calibration of the other liquid density transducers.

Disadvantages

(i) Hydrostatic densitometers must be installed horizontally on a solid base.
(ii) They are not flexible enough to adapt for any process. Thus, the process must be designed for it.

Applications

(i) Hydrostatic densitometers are suitable for solid and liquid density measurements only.
(ii) The hydrostatic weighing methods of liquids give continuous readings for two phase liquids such as slurries, sugar solutions, powders, etc.

Balance Type Densitometer

Working and Construction Balance type densitometers are based on gravity and/or weighing principles, and they are suitable for liquid and gas density measurements. Manufacturers offer many different types of balance densitometers. However, the most commonly used are

(i) Balanced-flow vessel methods
(ii) Buoyancy hydrostatic-weighing methods
(iii) Chain balanced float methods
(iv) Buoyancy gas balance methods

Balanced-flow vessel methods: In this type of densitometers a fixed volume vessel is employed for the measurements, as shown in Fig. 9.9. While the liquid or gas is flowing continuously through the vessel, the total assembly is weighed automatically by a sensitive scale, a spring balance system, or a pneumatic force balance transmitter. Since the volume and the weight of the fluid are known, the density or specific gravity can easily be calculated and scaled in respective units. In the design process, extra care must be exercised for the flexible end connections.

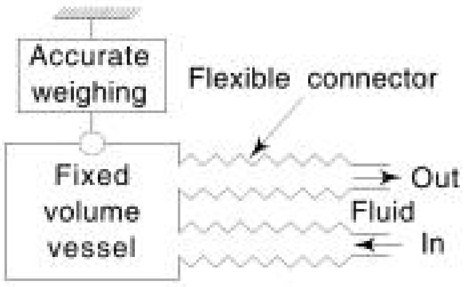

Fig. 9.9 *Balanced-flow Vessel Densitometer*

Buoyancy hydrostatic-weighing methods: The buoyancy method basically uses Archimedes' principle which states that a body immersed in a liquid is buoyed

Working and Construction Hydrometers use buoyancy principle as the main technique of operation. According to Archimedes' principle, when a body is immersed in a fluid, it loses weight equal to the weight of the liquid which is displaced. The hydrometer element is a constant-weight body which, if immersed in fluids with differing densities, will displace different volumes of fluid. Therefore, the degree of stem scale submersion is an indication of fluid density. Readings are made at the point where the steam emerges from the liquid. The accuracy of the measurement is a function of surface tension, turbulence, and sample contamination, all of which affect reading accuracy.

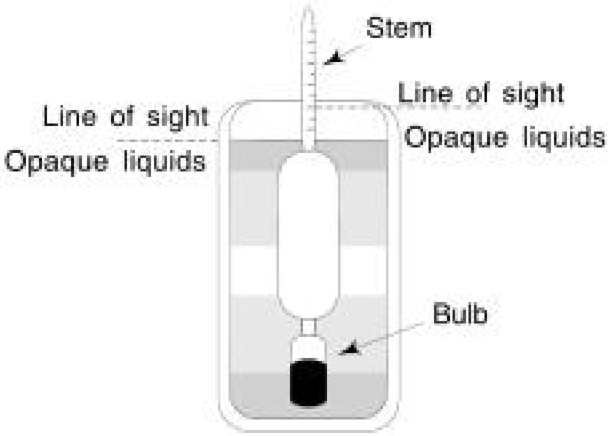

Fig. 9.14 *Hydrometer*

Almost all hydrometers are made from high grade glass tubing. The volume of fixed mass is converted to a linear distance by a sealed bulb shaped glass tube containing a long stem measurement scale, as shown in Fig. 9.14. The bulb is ballasted with a lead shot and pitch, the mass of which is dependent on the density range of the liquid to be measured. The bulb is simply placed into the liquid, and the density is read from the scale. The scale may be graduated in density units such as kg/m^2. Hydrometers can be calibrated for different ranges for surface tensions and temperatures. Temperature corrections can be made for set temperature such as 15 °C, 20 °C, 25 °C. ISO 387 covers a density range of 600 to 2000 kg/m^3.

Hydrometers may be classified according to the indication provided by graduations of the scale such as

(i) Density hydrometers
(ii) Specific gravity hydrometers
(iii) Percentage hydrometers showing the percentage of solution, e.g.
  (a) Sugar scale hydrometers
  (b) Arbitrary scale hydrometers.

Customized scales are also available; for example, lactometers for testing milk, alcoholmeters for alcohol levels, etc. Many other alternative scales are offered by manufacturers such as specific gravity, API gravity, Brix, Brine, etc.

The best way to read a hydrometer in clear liquids is to start with the eyes slightly below the plane of the liquid surface, and slowly raise the eyes until the surface of liquid appears as a straight line. The place where the line crosses the scale is the reading. With opaque liquids, such as oils, it is necessary to read the hydrometer at the top of the meniscus.

For accurate readings, the stem must be absolutely clean. Also, the surface of the liquid must be clean and free of dust. With precision grade hydrometers and with long small diameter stems, density values may be read to 0.0001. In general use of hydrometers, the uncertainty of readings may be in the region of ±0.01.

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9.3 VISCOSITY MEASUREMENT

Viscosity is a property of fluid which affects its behavior. If a fluid is defined as being a substance undergoing continuous deformation when subjected to a shear stress, then the consistency can be termed as the resistance offered by the fluid to such deformation. If static pressure and temperature are fixed, the consistency is constant for gases and Newtonian liquids and is called absolute viscosity. The consistency of non-Newtonian fluids varies even though the static pressure and temperature are fixed, a function of the applied shear stress. In some cases, the consistency may vary with duration of the applied shear stress. The consistency of non-Newtonian fluids is frequently expressed in terms of apparent viscosity. Thus, the viscometer is an instrument which measures consistency of gases, and Newtonian and non-Newtonian fluids.

Newtonian substances can be classified as fluids which exhibit constant ratio of shear stress rate when subjected to a shear and undergoing continuous deformation. Fluids that do not exhibit constant ratio of shear stress to shear rate are classified as complex fluids or non-Newtonian fluids. Most fluids of industrial importance can be classified as non-Newtonian such as liquid detergents, multigrade oils, paints, printing inks, and molten plastics.

In the *Principia* published in 1687, Sir Isaac Newton postulated that *the resistance which arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which parts of the liquid are separated from one another*. This *lack of slipperiness* is what we now call *viscosity*.

If τ is the relevant shear stress producing the motion and γ is the velocity gradient, we have

$$\tau = \mu \gamma \tag{9.40}$$

where, μ is sometimes called the coefficient of viscosity, but it is now more commonly referred as the viscosity. An instrument designed to measure viscosity is called a viscometer.

The SI units of viscosity are the pascal second = 1 $\mathrm{Nsm^{-2}}$ (= 1 $\mathrm{kg\ m^{-1}\ s^{-1}}$) and $\mathrm{Nsm^{-2}}$. The c.g.s. unit is the poise (= 0.1 $\mathrm{kg\ m^{-1}\ s^{-1}}$) or the poiseuille (= 1 $\mathrm{Nsm^{-2}}$). The units of kinetic viscosity v (=μ/ρ, where ρ is the density) are $\mathrm{m^2\ s^{-1}}$. The c.g.s. unit is the stokes (St) and 1 cSt = $10^{-6}\ \mathrm{m^2\ s^{-1}}$.

For simple liquids like water, the viscosity can depend on the pressure and temperature, but not on the velocity gradient (i.e. shear rate). If such materials satisfy certain further formal requirements (e.g. that they are inelastic), they are referred to as *Newtonian* viscous fluids. Most viscometers were originally designed to study these simple Newtonian fluids. It is now common knowledge, however, that most fluid-like materials one meets in practice have a much more complex behavior and this is characterized by the adjective *non-Newtonian*. The most common expression of non-Newtonian behavior is that the viscosity is now dependent on the shear rate γ and it is usual to refer to the apparent viscosity $\mu(\gamma)$ of such fluids.

In modern science and in processing plants, viscosity measurements are used in determining the following:

(i) Flowability of fluids

(ii) Concentration, size, and shape of solids in a slurry

(iii) Molecular weight and its distribution in high molecular weight substances

(iv) Color (of inks).

the fluid causes the liquid to flow through the capillary. A clock for measuring the efflux time of the fixed liquid volume and a thermostatic device completes the apparatus. Various modifications of the classical Ostwald device are available to suit various application needs.

For measuring kinematic viscosity, a sample liquid of fixed volume is charged to the lower receiving vessel and the viscometer is placed in a thermostatic bath. After time is allowed for the sample liquid to reach thermal equilibrium (about 5 minutes), the sample is drawn up into the efflux vessel by suction until the level is above the upper etched index line. The fluid is then permitted to flow down through the capillary by releasing the suction. When the fluid surface passes the upper etched index line, a stopwatch is started. The watch is stopped when the surface passes the lower etched index line of the efflux vessel. From this efflux time t, the kinematic viscosity of the fluid is calculated by multiplying it by the viscometer calibration constant.

Advantages

(i) Capillary-tube viscometer is a simple and convenient instrument for measuring kinematic viscosity accurately in the range of 0.2 to 12,000 centistokes.
(ii) With controlled temperature, it is capable of very accurate measurements.
(iii) It is relatively inexpensive.
(iv) It is easy to operate.
(v) It needs little or no maintenance besides cleaning.
(vi) It has high repeatability.

Disadvantages

(i) Because of the small driving force caused by the hydrostatic head of the fluid and because of the change in hydrostatic head with time, the capillary-tube viscometer is usually restricted to low-viscosity Newtonian fluids.
(ii) Since the unit is normally operated under vented (atmospheric) conditions, and because the time lag from sample taking to measurement is large, its use on highly evaporative or hydroscopically deteriorative samples is avoided.

Applications

(i) Kinematic viscosity measurements.
(ii) Measurement of low-viscosity Newtonian fluids.
(iii) Intrinsic viscosity determination.
(iv) Molecular weight measurements by relating it to intrinsic viscosity.
(v) Study of molecular shapes of natural and synthetic polymers.

9.3.2 Efflux Cup Viscometers

Efflux cup viscometers are most commonly used for fieldwork to measure the viscosity of oils, syrups, varnish, lacquer, paints, and bitumen emulsions, although they have some inherent inaccuracies. The testing procedure of efflux viscometer is quite similar to the capillary-tube viscometers where efflux time of a specified volume of fluid is measured through fixed orifice at the bottom of a cup

9.3.5 Applications of Viscometers

Viscosity measurement is done for the following applications:

(i) Viscosity is a direct measurement of fluid characteristics and behavior when in motion. It is very difficult to size a pump, pipeline, orifice meter, or agitator without knowing the viscosity of the process fluid. In any operation where liquids are used (spraying, coating, or dipping processes), viscosity of the fluid determines the effectiveness of the process and the quality for the finished product. In short, viscosity is one of the most important process properties.

(ii) Viscosity detection can be a sensitive indirect measurement of other properties. Molecular weight and its distribution in polymers, lubricating oils, and other substances, as well as the concentration, specific gravity, color, size, shape, and distribution of solids in a slurry or in an emulsion can all be reflected in viscosity variations.

(iii) Viscometers are used for determination of finished product specification.

(iv) They are used for routine laboratory testing. Simple-to-operate, easy-to-clean, and direct-reading viscometers are used for this purpose.

(v) They are used for scientific research study.

(vi) They are used for in-line process control purposes.

An orientation table for viscometers is shown in Table 9.3.

9.4 pH MEASUREMENT

9.4.1 Working Principle

As proposed by SPL Sorenson in 1909, pH, or a hydrogen ion exponent in a solution is given as

$$pH = -\log_{10} [H^+] = \log_{10} \frac{1}{[H^+]} \tag{9.43}$$

Thus pH, may be defined as negative logarithmic to base 10 of the reciprocal of the hydrogen ion concentration. It is a measure of the acidity or alkalinity of solution. All values of acidity and alkalinity with respect to hydrogen and hydroxyl ions can be expressed by a series of positive numbers between 0 and 14. Thus, a natural solution (like pure water) with $[H^+] = 10^{-7}$ has a pH of 7. If the pH is less than 7, the solution is acid, if greater than 7, the solution is alkaline. Therefore, pH scale can range from 0 to 14 in which the pH value lies between 0 to 7 for acidic solutions and between 7 to 14 for alkaline solutions.

pH measuring devices measure the effective concentration, or activity, of the hydrogen ions and not the actual concentration. In very dilute solutions of electrolyte the activity and concentration are identical. As the concentration of electrolyte in solution increases above 0.1 mol/litre, the measured value of pH becomes a less reliable measure of the concentration of hydrogen ions. In addition, as the concentration of a solution increases, the degree of dissociation of the electrolyte decreases.

In *liquid ion exchange electrodes*, as shown in Fig. 9.20(d), a porous layer containing an organic liquid of low water solubility separates the internal reference solution and the measured solution. Dissolved in the organic phase are large molecules in which the ions of interest are incorporated. The most important of these electrodes is the calcium electrode, but other electrodes in this class are available for the determination of Cl^-, ClO_4^-, NO_3^-, Cu^{2+}, Pb^{2+}, and BF_4^- ions. The liquid ion exchange electrodes have more chemical and physical limitations than the glass or solid state electrodes but they may be used to measure ions, which cannot yet be measured with a solid state electrode.

Gas-sensing membrane electrodes are not true membrane Electrodes as no current passes across the membrane. They are complete electrochemical cells, monitored by anion-selective electrode as the internal chemistry is changed by the ion being determined passing from the sample solution across the membrane to the inside of the cell. Example of this type of electrode is an ammonia electrode as shown in Fig. 9.20(e). The sensing surface of a flat-ended glass pH electrode is pressed tightly against a hydrophobic polymer membrane which is acting as a seal for the end of a tube containing ammonium chloride solution. A silver/silver chloride electrode is immersed in the bulk solution. The membrane permits the diffusion of free ammonia (NH_3), but not ions, between the sample solution and the film of ammonium chloride solution. The introduction of free ammonia changes

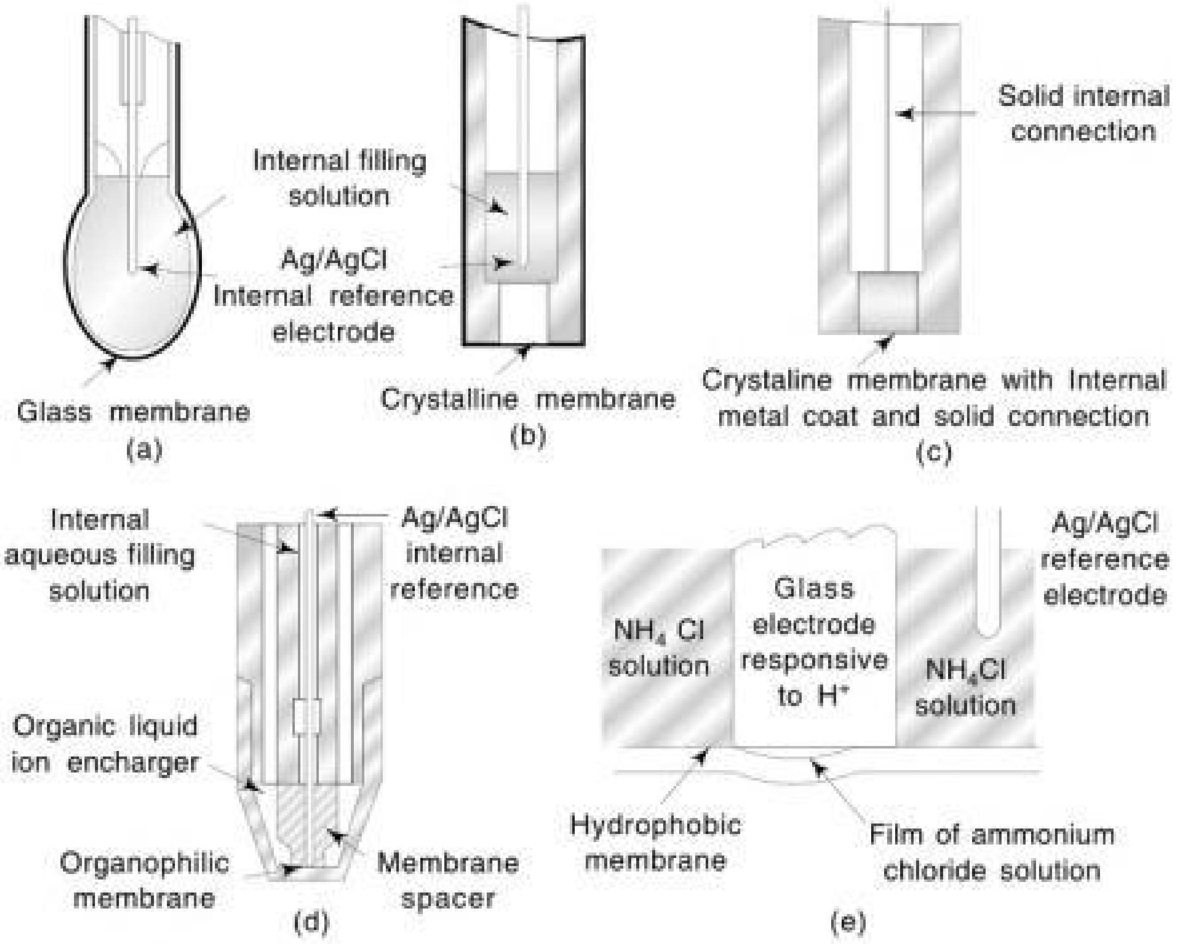

Fig. 9.20 *Ion-selective Electrodes (a) Glass, (b) Crystalline Membrane with Internal Reference Electrode, (c) Crystalline Membrane with Solid Connection, (d) Liquid Ion Exchange, and (e) Gas Sensing Membrane*

SELF-CHECK QUIZ

A. Tick (✓) the appropriate answer:-

1. Density applies to a substance in
   - (a) solid state (b) liquid state
   - (c) gas State (d) all of the three
2. Density of a substance is defined as
   - (a) volume of the substance (b) mass per unit volume
   - (c) mass per unit volume at fixed conditions (d) none of these
3. A process fluid having $0.87^{80/40}$ specific gravity means that
   - (a) the liquid at 80 °F will have a density of 0.87 times that of water at 40 °F
   - (b) the liquid at 40 °F will have a density of 0.87 times that of water at 80 °F
   - (c) both of these
   - (d) none of these
4. The density of acids and of light and heavy syrups is expressed in
   - (a) Barkometer degrees (b) Baume degrees
   - (c) Brix degrees (d) weight percentage
5. The purpose of density measurement is to
   - (a) determine the mass and volume of the substance (product)
   - (b) assess the quality of the product
   - (c) to determine the concentration or composition of a process stream
   - (d) all of these
6. Magnetic method of density measurement is used for
   - (a) both solids and gases (b) both solids and liquids
   - (c) both liquids and gases (d) all of these
7. Vibrating densitometer is used for density measurement of
   - (a) both solids and gases (b) both solids and liquids
   - (c) both liquids and gases (d) all of these
8. Bellows are used in the sensor tube of vibrating tube densitometer to
   - (a) isolate the sensors from external vibrations
   - (b) minimize the end loadings due to differential expansion and installation stresses
   - (c) both (a) & (b)
   - (d) none of these
9. Coriolis densitometer can be used to measure
   - (a) density of process fluid (b) flow rate of process fluid
   - (c) density and flow rate of solids (d) both (a) & (b)
10. Balance-type densitometers are suitable for density measurements of
    - (a) liquids and gases (b) gases only
    - (c) liquids only (d) solids only

10.4.1 Construction

Hook-type level indicator consists of a wire of corrosion resisting alloy (such as stainless steel) about $\frac{1}{4}$ in (0.063 mm) diameter, bent into U-shape with one arm longer than the other, as shown in Fig. 10.1. The shorter arm is pointed with a 60° taper, while the longer one is attached to a slider having a Vernier scale, which moves over the main scale and indicates the level.

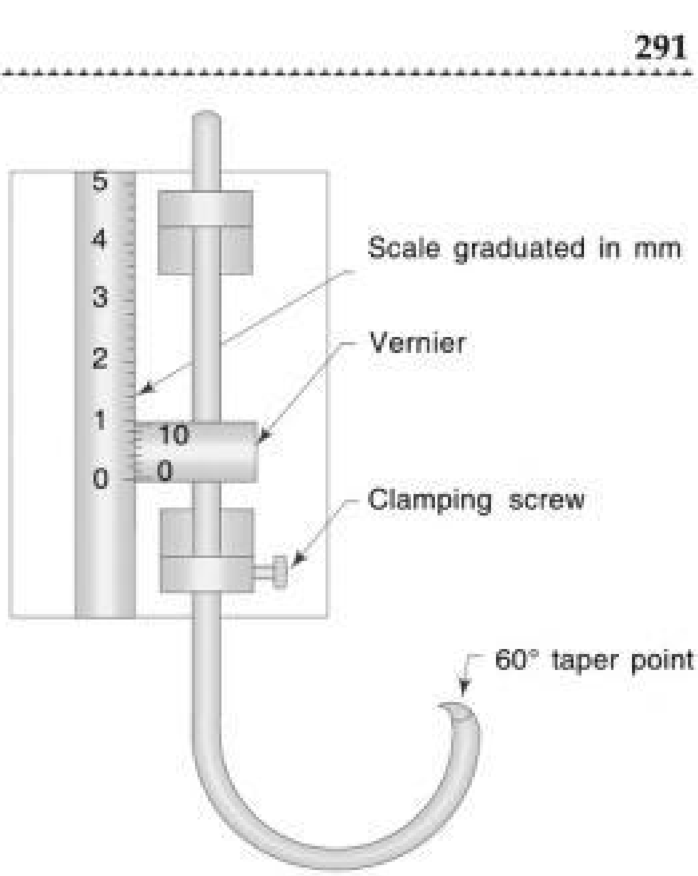

Fig. 10.1 *Hook-type Level Indicator*

10.4.2 Working

In hook-type of level indicator, the hook is pushed below the surface of liquid whose level is to be measured and gradually raised until the point is just about to break through the surface. It is then clamped, and the level is read on the scale. This principle is further utilised in the measuring point manometer in which the measuring point consists of a steel point fixed with the point upwards underneath the water surface. An eyepiece is fixed to view this point at 45° under water so that in addition to the point being seen, the image of the point by total internal reflection is also seen, as shown in Fig. 10.2. Now, the water level is adjusted until the tip of the image touches the tip of the point and the level is read on the scale. Since the point is always under water, the trouble due to the surface tension, when the point is above the water, is not experienced.

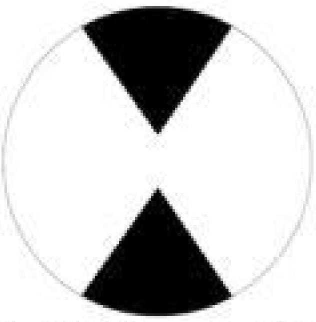

Fig. 10.2 *Measuring Point Manometer*

10.5 SIGHT GLASS

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

10.5.1 Construction and Working

A sight glass instrument consists of a graduated tube of toughened glass which is connected to the interior of the tank at the bottom in which the water level is required. Figure 10.3 shows a simple sight glass for an open tank in which the liquid level in the sight glass matches the level of liquid in the tank. As the level

10.7 DISPLACER LEVEL DETECTORS

The displacer-type level detectors work on the Archimedes' principle which states that a body, wholly or partially immersed in fluid, is buoyed up by a force which is equal to the weight of the fluid displaced. If the cross-sectional area of the displacer and the density of the liquid are constant, then a unit change in level will result in a reproducible unit change in the displacer weight. By detecting the apparent weight of the immersed displacer, the level of the fluid is measured.

The simplest level measuring device of this type consists of a displacer that is heavier than the process liquid and is suspended from a spring scale. When the liquid level is below the displacer, the scale shows the full weight of the displacer. As the level rises the apparent weight of the displacer decreases, thereby yielding a linear and proportional relationship between the spring tension and level. The spring scale can be calibrated 0 to 100 per cent, or in other level units. But this simple device is limited to the applications in open tanks. In actual industrial liquid level measurement, the basic problem is to seal the process from the spring scale or other force detecting mechanism. This seal has to be frictionless and useful over a wide range of pressures, temperatures, and corrosion conditions.

The various types of displacer level detectors are defined, based on the variations in the design of the seal which are listed below.

(i) Magnetically-coupled switch type
(ii) Torque tube type
(iii) Diaphragm and force bar type
(iv) Spring balanced type
(v) Flexible disc type
(vi) Flexible shaft type

All of the above types operate on Archimedes' principle, but are different as far as their scales are concerned. All of them can detect liquid-vapour interface, liquid-liquid interface and if level is constant, they can be used to detect density changes.

A torque-tube type displacer for liquid level measurement is shown in Fig. 10.7. It consists of a cylindrical displacer which can be furnished in a wide length of plastic and alloy materials. Although any length displacer upto 3m can be obtained, the most common lengths used are 0.3, 0.8, 1.2 and 1.5 m. The volume of the standard displacer is 1638 cc and consequently the diameter is reduced as the length increases. A hollow torsion tube (or torque tube) is used to both support the displacer, which is always heavier than the process fluid, and to provide a frictionless pressure seal. This makes it possible to transfer the changes in the apparent weight of the displacer through the wall of the pressure vessel into a suitable measuring device. The displacer is connected to the torque tube by the help of a torque arm which absorbs lateral forces. Friction is minimized by use of a knife-edge bearing support as shown in Fig. 10.7. A limit stop is attached with the torque arm to prevent accidental over-stressing of the torque tube by limiting the downward motion of the torque arm. A torque rod is placed in the torque tube which is attached with a flapper-nozzle assembly. The angular displacement of the

the tubing to the pressure indicator. When the tank is empty, the sealed air is uncompressed and corresponds to zero on the pressure indicator. As the tank is filled with liquid, the head of liquid in the tank flexes the bellows, which compresses the air above the bellows. The compression of sealed air is transmitted to the indicator which is calibrated in terms of the tank liquid level. Air bellows may be constructed for various applications and ranges. Figure 10.10 shows an industrial application of air bellows in which a closed-box air bellows is connected to the process fluid tank via a seal, for liquid level measurement. Here, liquid seals are used while measuring corrosion or viscous liquids level.

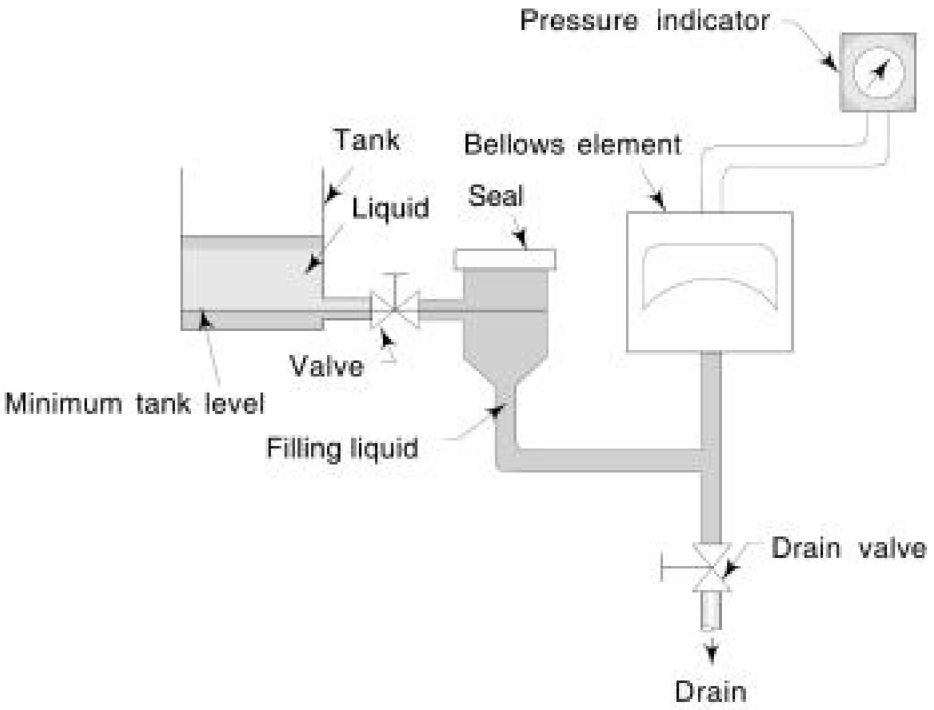

Fig. 10.10 *A Closed-box Air Bellows Connected to the Pressure Fluid Tank*

10.12 AIR PURGE SYSTEM

Air purge (also known as bubbler tube) system is one of the most popular hydrostatic pressure type of liquid level measuring system which is suitable for any liquid as shown in Fig. 10.11.

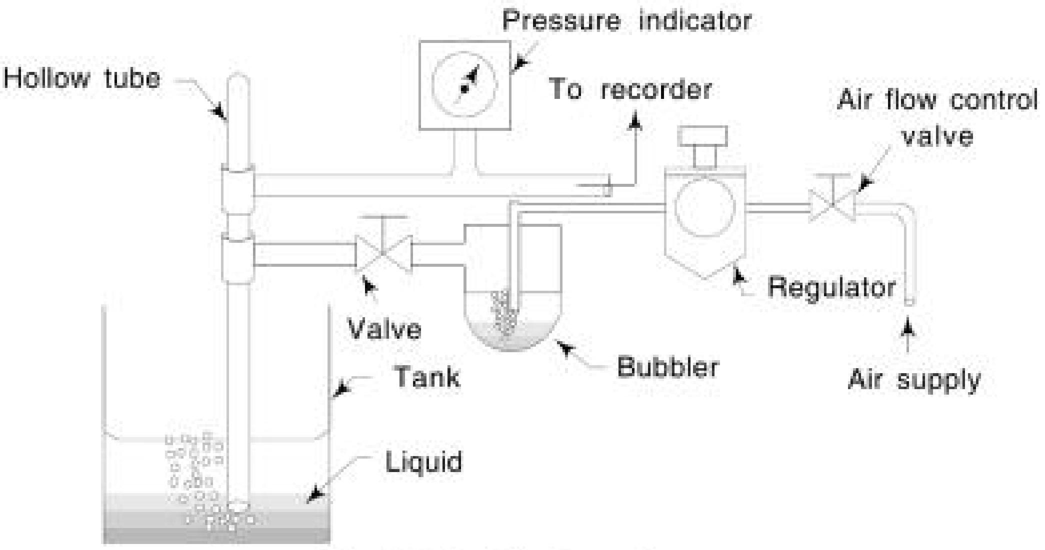

Fig. 10.11 *Air Purge System*

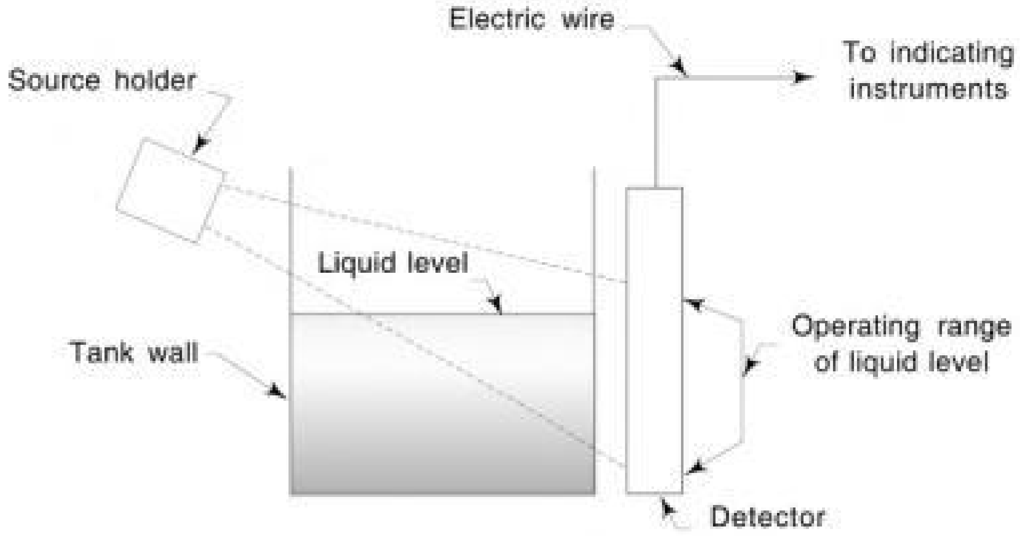

Fig. 10.13 *Radiation Type Level Indicator*

The amount of radiation received is inversely proportional to the amount of liquid between the radiation source and the detector. The difference in the amount of radiation received by the detector, corresponds to the liquid level in the tank. Thus, when liquid level rises, the amount of radiation received is reduced and vice versa. The radiation loss received by the tank walls is constant whether the tank is full or empty.

10.16.2 Advantages

Following are the advantages of radiation level indicators:

(i) There is no physical contact with the liquid.
(ii) They are suitable for molten metals as well as liquids of all types (corrosive, abrasive, highly viscous, adherent).
(iii) They are useful at very high temperatures/pressures.
(iv) They have good accuracy and response.
(v) They have no moving parts.

10.16.3 Disadvantages

Following are the disadvantages of radiation level indicators:

(i) The reading is affected by density change of liquid.
(ii) Radiation sourceholders may be heavy.
(iii) Their cost is relatively high.

10.17 LASER LEVEL SENSORS

10.17.1 Working and Construction

Laser-based level measurement depends on the accurate detection of the time it takes for a light pulse to travel to the process material surface and back. The velocity of light is affected by the index of refraction of the vapors through which the light pulse travels. The velocity of light in a gas or vapor is given as

$$C = \frac{C_0}{N} \tag{10.5}$$

There are various microwave level switches that are used for liquid or liquid level measurements such as

(i) Reflection level switches

(ii) Beam-breaker level switches

Reflection Level Switches In *microwave reflection level switches*, the changes in the amplitude and/or phase of the reflected signal is used to determine material presence. Figure 10.16 illustrates the working of a reflector level switch. Reflection is proportional to the dielectric constant of the material immediately next to the process window. The microwave signal is generated by the microwave generator and strikes the material surface in the tank through the microwave window. The reflected beam is received by the microwave detector and it compares the return signal to a reference signal in a balanced bridge circuit to provide additional sensitivity. This helps the detector to recognize low dielectric materials such as plastic pellets (dielectric of 1.1).

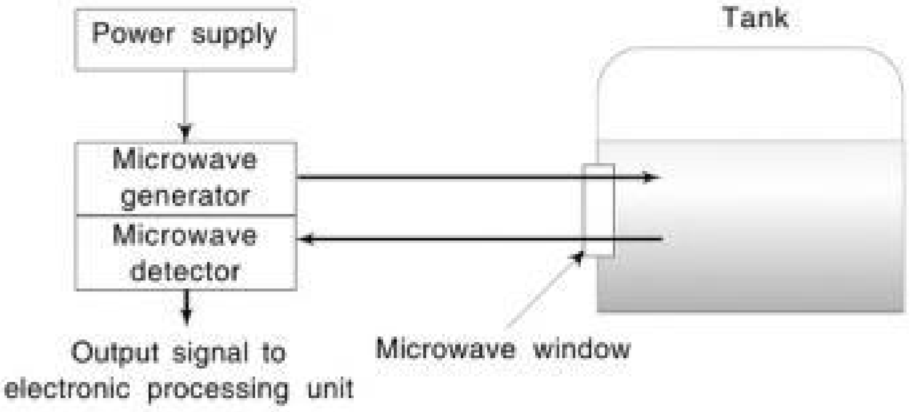

Fig. 10.16 *Microwave Reflection Level Detector*

Microwave reflection level switches are useful for liquid-liquid interface and liquid-solid interface detection on materials that have as little as 0.1 difference in dielectric constant. On solid applications, the reflection technique is limited to detecting particles with diameters less than 6 mm for an X-band detector and to 2.5 mm for a K-band detector. Above this size, the particles begin to scatter the beam and reduce the amount of signal that is reflected directly to the detector.

The reflection type of microwave detector is simpler to install and to start up. It is useful on granular solids and powders such as limestone, carbon black, and pelletized materials where it has advantages in terms of abrasion and coating resistance, as well as having no mechanical part in the vessel that can be broken or pulled off. It is also useful for difficult-to-handle liquids that are viscous, toxic, or hazardous because the detector is isolated from the vessel contents.

Figure 10.17 shows the microwave reflection characteristics of different materials. Air, other gases, and foam have a low dielectric constant and return little or no signal. Materials with high dielectric constants, such as water, tend to return all of the signals.

Beam Breaker Level Switches In *microwave beam-breaker level switches*, a beam is sent across the measurement zone, as shown in Fig. 10.18. When air or vapour is in this zone, a strong signal is received at the detector. When process material breaks the beam path, it reduces the signal received at the detector due to

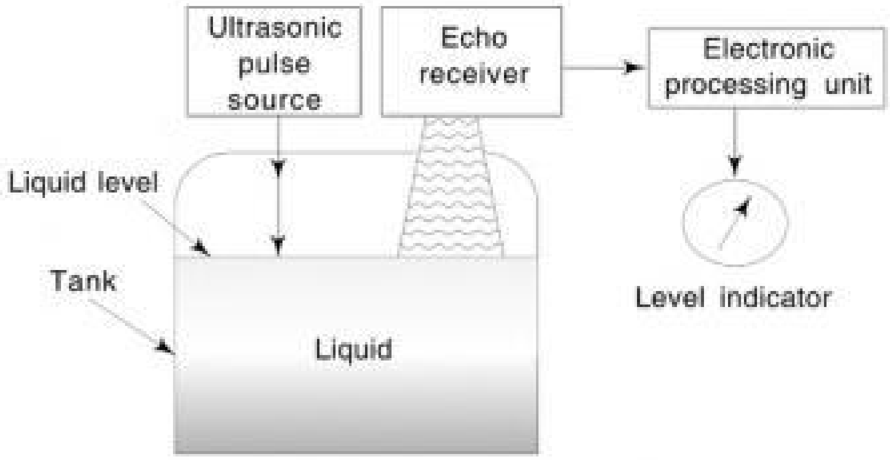

Fig. 10.21 *Ultrasonic Level Detector*

characteristics as they tend to absorb the sonic pulse. Since the angle of reflection is equal to the angle of incidence, it is important that the reflecting surface be flat. If the sonic pulse is reflected from a sloping surface, its echo will not be directed back to the source and the round-trip travel time will not accurately reflect the vertical distance. Irregular surfaces result in diffuse reflection where only small portions of the total echo travels vertically back to the source.

Ultrasonic level measuring devices can be used for both continuous and point measurements. The point measuring ultrasonic detectors are used for measurement of gas/liquid, liquid/liquid, or gas/solid interfaces.

10.20.2 Advantages

Following are the advantages of ultrasonic level detectors:

(i) Ultrasonic level detectors are non-contact type measurement techniques. They have the ability to measure level without making physical contact with the process material.

(ii) They have no moving parts.

(iii) The reliability of the reading is unaffected by changes in the composition, density, moisture content, electrical conductivity, or dielectric constant of the process fluid.

10.20.3 Disadvantages

Following are the disadvantages of ultrasonic level detector:

(i) An ultrasonic transmitter is subject to many interferences, which affect the strength of the echo it receives. The echo can be weak due to dispersion (which reduces sound intensity by the square of distance) and absorption (which in dry air reduces its energy level).

(ii) Temperature compensation is essential in ultrasonic level measurement.

(iii) The dirt, irregular and slope surfaces affect the accuracy of the measurement.

10.21 EDDY CURRENT LEVEL MEASUREMENT SENSORS

10.21.1 Working and Construction

An eddy current level sensor uses the eddy-current principle to measure the level of molten (liquid) metals or other conducting liquids in a tank. It consists of three

Table 10.2 *Orientation Table for Level Sensors*

Type	Level Range	Max. Temperature (°F) °C = (°F – 32)/1.8	Available as Noncontact	Inaccuracy (1 in = 25.4 mm)	Cost			Available Designs			Applications								Limitations
											Liquids					Solids			
	In feet 1 3 6 12 24 48 96 100 150 200 0.3 1 2 4 8 16 32 34 50 67 In meters				Under $1000	$1000–$5000	Over $5000	Switch	Local Indicator	Transmitter	Clean	Viscous	Slurry/Sludge	Interface	Foam	Powder	Chunky	Sticky	
Air Bubblers		UL		1–2% FS	✓			✓	✓	✓	G	F	P	F					Introduces foreign substance into process: high maintenance.
Capacitance		2,000	✓	1–2% FS	✓	✓		✓		✓	G	F-G	F	G-L	P	F	F	P	Interface between conductive layers and detection of foam is a problem
Conductivity Switch	Points Sensor	1800		1/3 in.	✓			✓			F	P	F	L	L	L	L	L	Can detect interface only between conductive and nonconductive liquids. Field effect design for solids.
Diaphragm		350		0.5% FS	✓	✓		✓		✓	G	F	F			F	F	P	Switches only for solids service.
Differential Pressure		1200		0.1% AS	✓	✓		✓	✓	✓	E	G-E	G	P					Only extended diaphragm seals or repeaters can eliminate plugging. Purging and sealing legs are also used.
Displacer		850		0.5% FS	✓	✓		✓	✓	✓	E	P	P	F-G					Not recommended for sludge or slurry service.
Float		500		1% FS	✓			✓	✓	✓	G	P	P	F					Moving parts limit most designs to clean service. Only preset density floats can follow interfaces.
Laser		UL	✓	0.5 in			✓			✓	L	G	G		F	F	F	F	Limited to cloudy liquids or bright solids in tanks with transparent vapor spaces.
Level Gauges		700		0.25 in.	✓				✓		G	F	P	F					Glass is not allowed in some processes.

(*Contd.*)

10. Ultrasonic level transmitters operate by generating _______ and measuring the ______ taken for the echo to return.

C. State True/False:-

1. The slight glass level indicator is read where the tank is located.
2. In case of a float type level indicator, it is not possible to read the liquid levels in a tank from the ground level if the tank is kept below the ground level or above the ground level.
3. Air bellows are used for liquid level measurement where an indicator can be conveniently located at the specified datum line.
4. In radiation level detectors, it does not need to come in contact with the liquid being measured.
5. Only light mineral oil, not the water, is used as the purge liquid in liquid purge system of level indication.
6. The purge liquid of liquid purge system of level indication should not vaporize at the temperature of the pipe lines.
7. In laser level sensors, the angle change of the beam is reduced with increasing distance, which also reduces the accuracy of the instrument.
8. The beam-breaker microwave level detectors use very large antennas.
9. In case of fiber-optic level measurement probe, when there is no liquid on the fiber, the return beam has the same intensity as the source beam.
10. Measurement accuracy is decreased for slope (inclined) surface when using ultrasonic level sensors.

REVIEW QUESTIONS

1. What is the most common low level industrial level indicator? How does it work?
2. Describe any method of liquid level measurement for measuring the level of a corrosive liquid.
3. Describe with a neat sketch, the method of molten liquid level measurement in a continuous casting shop of steel plant.
4. Describe with a sketch, method by which the level of water in a boiler drum can be indicated at a point some 209 meters away.
5. List the various types of solid level measurement systems used in an industry. Describe in detail the working and construction of any two of them.
6. Describe with a neat sketch the construction and working of a radiation level indicator.
7. (a) Describe with diagram a system for remotely indicating the level of an electrically conducting liquid in a metal vessel employing an electrode.
   (b) Explain in what way the accuracy of indication of level might be affected by the following:
      (i) conductivity of the liquid in the vessel
      (ii) electric insulation of electrodes from wall of vessel
      (iii) length of the electrode from the vessel.

$$V = K\sqrt{\frac{2gh}{\rho}} \tag{11.1}$$

$$Q = KA\sqrt{\frac{2gh}{\rho}} \tag{11.2}$$

$$W = KA\sqrt{\frac{2gh}{\rho}} \tag{11.3}$$

where, V = velocity of flowing fluid
Q = volume flow rate
W = mass flow rate
A = cross-sectional area of pipe through which fluid is flowing
h = differential head (pressure) across the restriction element
g = acceleration due to gravity
ρ = density of the flowing liquid

$$K = \frac{C}{\sqrt{1-\beta^4}} = \text{a constant}$$

where C = discharge coefficient
β = diameter ratio

$$\beta = \frac{d\text{ (diameter of restriction element)}}{D\text{ (inside diameter of the pipe)}}$$

Reynolds Number Reynolds number is a very important reference number in the accurate determination of flow. It is used to determine the point at which the flow goes from the viscous to the turbulent stage. As the flow changes from viscous to turbulent and vice versa, there is a very marked change in the value of the flow coefficient, but there is very little change with further increase in speed. If very high degrees of accuracies are desired when head meters are employed, then corrections will have to be made for the Reynolds number. It was discovered by Osborne Reynolds in the late 1800s, and was named in his honour. Reynolds number is given by the equation,

$$R_D = \frac{VD\rho}{\mu} \tag{11.4}$$

where R_D = Reynolds number
V = average velocity
D = inside pipe diameter
ρ = density of flowing fluid
μ = absolute viscosity

Reynolds number is a dimensionless unit when consistent units are used in its determination.

Advantages of Differential Flowmeters The advantages of a differential flowmeter are:

(i) Its cost is relatively low especially for large lines.

(ii) It offers the widest applicational coverage of any type of meter.

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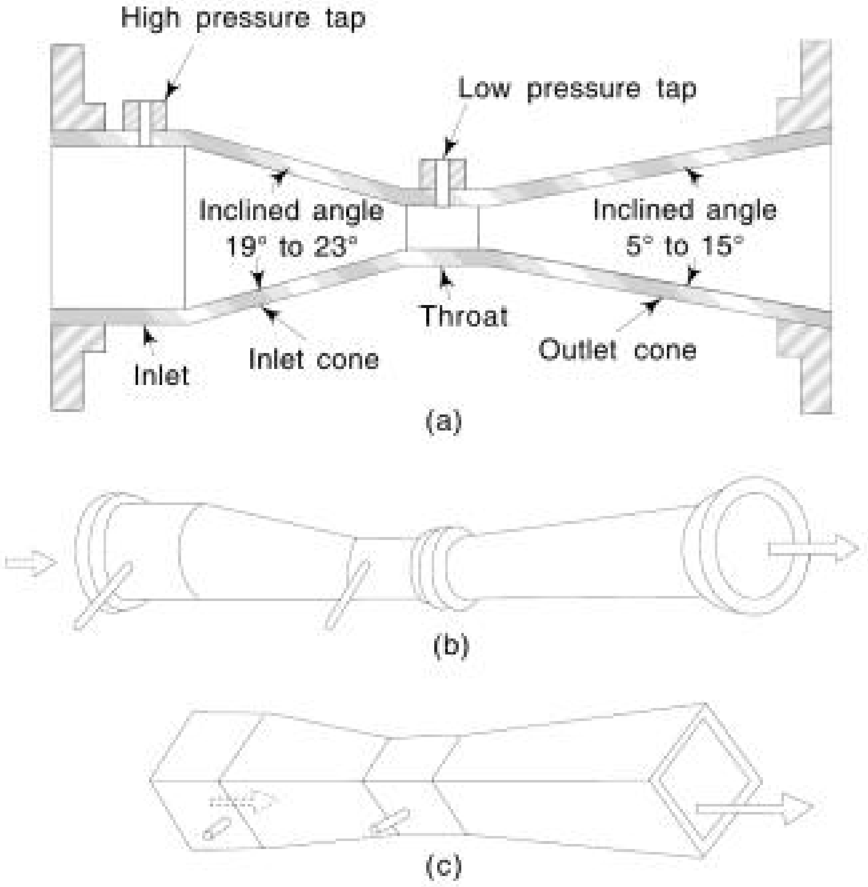

Fig. 11.3 *Venturi Tubes*
(a) Long-form or Classic Venturi Tube
(b) Eccentric Venturi Tube
(c) Rectangular Venturi Tube

(iv) It has well-known characteristics.
(v) It is more accurate over wide flow ranges than orifice plates or nozzles.
(vi) It can be used at low and high beta ratios.

Disadvantages The disadvantages of a venturi tube are:

(i) Its cost is high.
(ii) It is generally not useful below 76.2 mm pipe size.
(iii) It is more difficult to inspect due to its construction.
(iv) It has the limitation of a lower Reynolds number of 150,000, (Some data is however available down to a Reynolds number of 50,000 in some sizes).

Flow Nozzles The flow nozzles are used for flow measurements at high fluid velocities and are more rugged and more resistant to erosion than the sharp edged orifice plate. Basically, there are two types of flow nozzles, the long-radius flow nozzles and the I.S.A. (International Federation of the National Standardizing Associations) flow nozzle. A flow nozzle consists of a convergent inlet whose shape is a quarter ellipse, and a cylindrical throat, as shown in Fig. 11.4. Differential

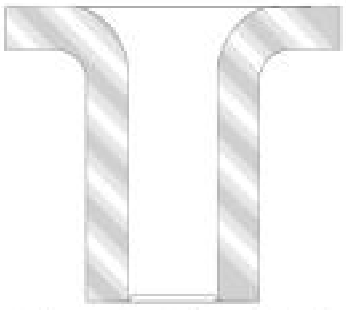

Fig. 11.4 *Flow Nozzle*

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The accuracy range of annubar tubes is from ±1/2 to 3/2%, and they are available in pipe sizes from 3.175 to 3750 mm.

Advantages The advantages of the annubar tube are:

(i) It is available for a wide range of pipe sizes.
(ii) It is simple and economical to install.
(iii) It provides negligible pressure drop.
(iv) It can be placed in service under pressure.
(v) It can be rotated while in service, for cleaning action.
(vi) It provides long-term measurement stability.

Disadvantages The disadvantages of the annubar tube are:

(i) It is unsuitable for operating dirty or sticky fluids.
(ii) It has limited operating data

Elbow Taps The flow measurement using elbow taps as a primary element, depends on the measurement of the differential pressure between the two points (the inside and outside curves of the elbow) developed by centrifugal force, as the direction of fluid flow is changed in a pipe line elbow. The taps are located at opposite ends of diameter in the plan of the elbow, and the diameter which passes through the tap is at either 45° or 22.5° from the inlet face of the elbow as shown in Fig. 11.8.

Elbow taps are rarely used. Its accuracy is poor, varying from ±5 to ±10%.

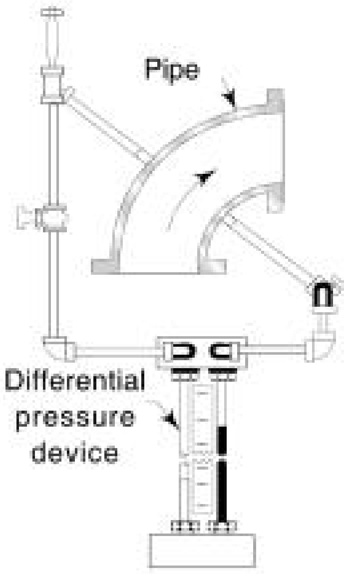

Fig. 11.8 *Elbow Tap*

Advantages The advantages of elbow taps are:

(i) The elbow taps are easy to add to existing installation where elbows exist.
(ii) Its cost is comparatively low.
(iii) It allows no additional pressure loss.
(iv) With the elbow taps there are no obstructions in the line.
(v) It has good repeatability.

Disadvantages The disadvantages of the elbow tap are:

(i) Its accuracy is poor.
(ii) Differential pressure developed is relatively small.

Weirs Weirs are used to measure flow rate primarily in open channels such as water works including irrigation, waste and sewage systems, and in pipes and conduits that are generally not completely filled with liquid. It is an obstruction in a flowing stream over which the liquid is made to pass. With the use of weir, flow rates can be measured from a few gallons per minute to millions of gallons per day. There are three types of weirs such as rectangular, V-notch and cippoletti or trapezoidal, as shown in Fig. 11.9.

made linear. As the weight of the piston is constant, the pressure differential is constant. The flow reading of the meter is transmitted using a reluctance-type transducer, as shown in Fig. 11.11.

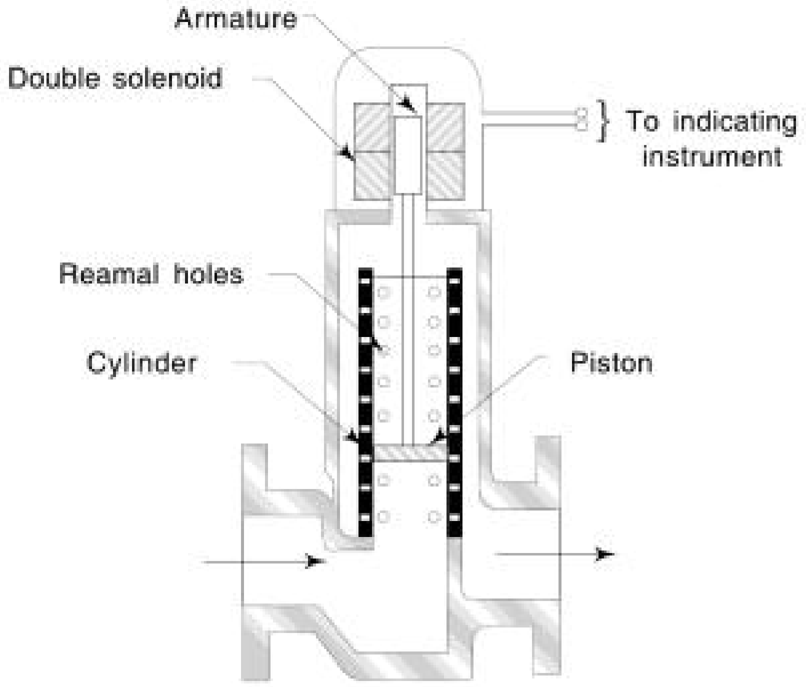

Fig. 11.11 *Cylinder and Piston Type Meter*

When fluid enters the cylinder, the piston exerts a constant downward force, and the difference in pressures between the two sides of the piston places the piston in a particular position. As the down stream flow is increased, the pressure on the load side of the piston is reduced. The increased differential pressure then forces the piston up, thereby increasing the area of the openings through which the fluid can flow until the pressure differential is again balanced. The linear movement of the piston in the cylinder is sensed by a linear variable differential transformer (LVDT) which converts this linear motion into voltage signal which is proportional to the flow rate.

These types of meters are used for high viscosity fluids materials which are corrosive or might clog lines, and materials whose flow coefficients are not well known.

Advantages The advantages of cylinder and piston type flowmeter are:

(i) It is good for high viscosity fluids.
(ii) It has good accuracy.
(iii) The range of such instruments can have wide variations.
(iv) It can be designed to use flow rates of the order of 0.08 cc/min where variable-head meters are not suitable.

Disadvantages The disadvantages of cylinder and piston type flowmeter are:

(i) Its cost is relatively high.
(ii) It has limited size range (about 25 to 100 mm).

11.3.3 Magnetic Flowmeters

Magnetic flowmeters are traditionally the first type of flowmeters to be considered for high corrosive applications and for applications involving measurement of

The flowing fluid impinges on the turbine blades (rotor), imparting a force to the blade surface which causes the rotation of the rotor. The speed of the rotor is directly proportional to the fluid velocity, and hence to volumetric flow rate when it is at a steady rotational speed. The speed of rotation is monitored in most of the meters by a magnetic-pickup coil, which is fitted to the outside of the meter housing. The magnetic-pickup coil consists of a permanent magnet with coil windings which is mounted in close proximity to the rotor but internal to the fluid channel. As each rotor blade passes the magnetic-pickup coil, it generates a voltage pulse which is a measure of the flow rate, and the total number of pulses give a measure of the total flow. The electrical voltage pulses can be totalled; subtracted and manipulated by digital techniques so that a zero error characteristic of digital handling is provided from the pulse generator to the final read out. The *K* factor (i.e. the number of pulses generated per gallon of flow) is given as,

$$K = \frac{T_K f}{Q} \tag{11.10}$$

where, K = pulses per volume unit
T_K = a time constant in min.
Q = a volumetric flow rate in gpm.
f = frequency in Hz

The turbine flow meters provide very accurate flow measurement over wide flow range. The accuracy range is from ±1/4 to ±1/2%, and the repeatability is excellent, ranging from ±0.25% to as good as ±0.02%. The rangeability of turbine meters are generally considered to be between 10 : 1 and 20 : 1, however, in low flow ranges, it is often less than 10 : 1. The military type turbine meters have achieved rangeabilities greater than 100 : 1. The turbine meters are available in sizes ranging from 6.35 to 60 mm and liquid flow ranges from 0.1 to over 50,000 gallons per minute.

The turbine meters are widely used for military applications. They are particularly useful in blending systems for the petroleum industry. They are effective in aerospace and airborne applications for energy-fuel and cryogenic (liquid oxygen and nitrogen) flow measurements.

Advantages The advantages of turbine flowmeter are:

(i) Its accuracy is good.
(ii) It provides excellent repeatability and rangeability.
(iii) It allows fairly low pressure drop.
(iv) It is easy to install and maintain.
(v) It gives good temperature and pressure ratings.
(vi) It can be compensated for viscosity variations.

Disadvantages The disadvantages of turbine flowmeter are:

(i) Its cost is high.
(ii) Its use is limited for slurry applications.
(iii) It faces problems caused by non-lubricating fluids.

The output voltage signal of this type of instrument is given by the equation,

$$E = \frac{C}{2(\pi K C_p \, \rho d V)^{1/2} + K} \tag{11.15}$$

where E = voltage generated
C = instrument constant
K = thermal conductivity of fluid
C_P = specific heat of fluid
d = diameter of heated thermocouple wire
V = velocity of fluid
ρ = density of the flowing fluid

Thermal flowmeters are used to measure the flow of liquid and gases in the range from 0.5 cm^3/min. to 18,000 kg/hr. Its accuracy is about ±2% of full scale, and it can be designed to work with pressure upto 1200 psig (8.3 MPa).

11.3.7 Vortex Flowmeters

Currently, there are three types of vortex flowmeters commercially available.

(i) Swirlmeter
(ii) Vortex shedding meter
(iii) Fluidic meter

Swirlmeters The swirlmeter operates on the principle of vortex precession. It is a digital volumetric device which has no moving parts. It gives an output in the form of pulses whose frequency is proportional to fluid flow rate.

Figure 11.17 shows the construction of a swirlmeter. It consists of a fixed set of swirl blades, usually made of stainless steel, which introduce a spinning or swirling motion to the fluid at the inlet. At the downstream of the swril blades there is a venturi-like contraction and expansion of the flow passage. A temperature sensor (e.g. thermistor) is placed at the downstream to the blades which is heated by a constant electric current. At the exit of the meter, deswirl blades are fixed to straighten out the flow leaving the meter, as shown in Fig. 11.17. Its purpose is to isolate the meter from downstream piping effects.

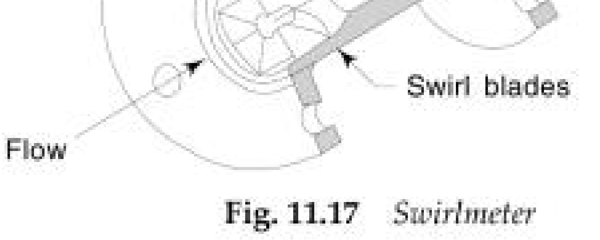

Fig. 11.17 *Swirlmeter*

As the fluid passes through the fixed set of swirl blades at the inlet, a swirling (or spinning) motion is imparted to it. In the area where expansion occurs, the swirling flow precedes or oscillates at a frequency proportional to the fluid flow rate. This

θ = angle of path with respect to the pipe axis

V = velocity of fluid in pipe

The time difference between T_{AB} and T_{BA} can be calculated as,

$$\Delta T = T_{AB} - T_{BA} = \frac{2\,LV\cos\theta}{C} \tag{11.18}$$

or,

$$V = \frac{\Delta T\, C}{2\,L\cos\theta} \tag{11.19}$$

Since, this type of flowmeter relies upon an ultrasonic signal traversing across the pipe, the liquid must be relatively free of solids and air bubbles.

Doppler Flowmeters In doppler flowmeter, an ultrasonic wave is projected at an angle through the pipe wall into the liquid by a transmitting crystal in a transducer mounted outside the pipe, as shown in Fig. 11.20(b). Part of the ultrasonic wave is reflected by bubbles or particles in the liquid and is returned through the pipe wall to a receiving crystal. Since the reflectors (bubbles) are travelling at the fluid velocity, the frequency of the reflected wave is shifted according to the Dopple principle. The velocity of the fluid is given by the equation:

$$V = \frac{\Delta f\, C_t}{2 f_0 \cos\theta} = \Delta f K \tag{11.20}$$

where Δf = difference between transmitted and received frequency

C_t = velocity of sound in the transducer

f_0 = frequency of transmission

θ = angle of transmitter and receiver crystal with respect to the pipe axis.

K = constant

Advantages of Ultrasonic Flowmeters The advantages of ultrasonic flowmeters are:

(i) It does not impose additional resistance to the flow or disturb the flow pattern as the transducers are inserted in the wall of pipe.

(ii) Its velocity/output relationship is linear.

(iii) It has no moving parts.

(iv) Its repeatability is in the order of 0.01%.

11.4 QUANTITY FLOWMETERS

Quantity flowmeters are used for the measurement of small percentage of industrial flow rate. These meters operate by passing the fluid to be measured through the meter in separate and distinct increments of alternately feeling and emptying containers of known fixed capacity. The number of times the container is filled and emptied gives the quantity of flow.

The quantity flowmeters may be divided in two categories:

(i) Positive displacement meters

(ii) Metering pumps

(iii) It is susceptible to damage from entrained vapours and dirty fluids.

(iv) Its accuracy decreases at low flow rates.

Reciprocating Piston Meters The reciprocating piston meter is the oldest of the positive displacement meters. It is widely used in petroleum industry. It is very similar in construction to a reciprocating steam engine piston and cylinder. It consists of a cast iron cylinder fitted with a piston, as shown in Fig. 11.24. Two slide valves are attached at the inlet and outlet ports. The fluid to be measured enters through the inlet forcing the piston to the left until the cylinder is full and piston is in its extreme left position. At this point, an external leakage causes both slide valves to move and thus the liquid enters the left cylinder forcing the piston to its extreme right position. When the cylinder becomes full, the slide valves again move and the cycle is repeated. The external arm of the slide valve drives a counter which provides a total of the fluid quantity that has passed through the meter. Instead of one piston, a number of pistons operating on a centre crank are generally incorporated with this type of meter.

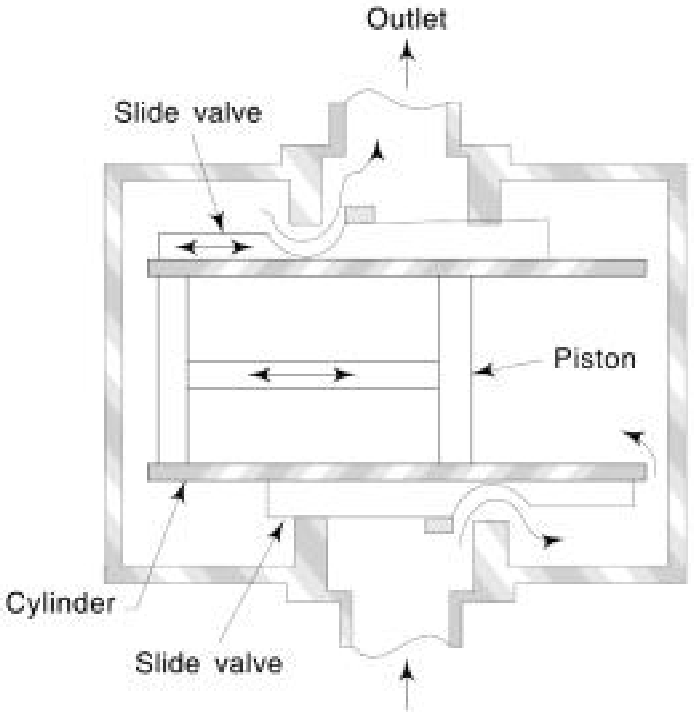

Fig. 11.24 *Reciprocating Piston Meter*

Reciprocating pump meters are available in many forms such as multi-piston meters, double-acting piston meters, rotary valves, and horizontal slide valves. The accuracy of these meters are from ±0.2 to ±0.3%.

Advantages The advantages of reciprocating piston meters are:

(i) Its accuracy is high.

(ii) Construction materials are not limited in reciprocating piston meters.

Limitations The limitations of reciprocating piston meters are:

(i) Their cost is relatively high.

(ii) They are subject to leakage.

(iii) Problems are created by dirty fluids.

(iv) It requires high maintenance cost.

(v) It is restricted to moderate flow rates.

(vi) It produces pulsating flow when used for liquid measurement.

Lobed Impeller Meters The lobed impeller meter is widely used in measuring and controlling of petroleum crudes and finished products. It consists of two lobed impellers which are geared to maintain a fixed relative position. These impellers rotate in opposite directions within the housing as shown in

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11.6 CALIBRATION OF FLOWMETERS

There are various methods available for the calibration of flowmeters and the requirement can be split into two distinct categories; (a) in situ and (b) laboratory. Calibration of liquid flowmeters is generally somewhat more straightforward than that of gas flowmeters since liquids can be stored in open vessels and water can often be utilized as the calibrating liquid.

11.6.1 Calibration Methods for Liquid Flowmeters

The main methods used for liquid flowmeter calibration are in-situ and laboratory.

In-situ Calibration Methods The in-situ calibration methods use (a) insertion-point velocity method, and (b) dilution gauging/tracer method.

Insertion-point Velocity Method It is one of the simpler methods of in-situ flowmeter calibration. It utilizes point-velocity measuring devices where calibration device chosen is positioned in the flowstream adjacent to the flowmeter being calibrated and such that mean flow velocity can be measured. In difficult situations a flow traverse can be carried out to determine flow profile and mean flow velocity.

Dilution Gauging/Tracer Method It can be applied to closed-pipe and open-channel flowmeter calibration. A suitable tracer (chemical or radioactive) is injected at an accurately measured constant rate and samples are taken from the flowstream at a point downstream of the injection point where complete mixing of the injected water will have taken place. By measuring the tracer concentration in the samples the tracer dilution can be established and from this dilution and the injection rate the volumetric flow can be calculated. Figure 11.29 illustrates the principle of dilution gauging by tracer method. Alternatively, a pulse of tracer material may be added to the flowstream and the time taken for the tracer to travel a known distance and reach a maximum concentration is a measure of the flow velocity.

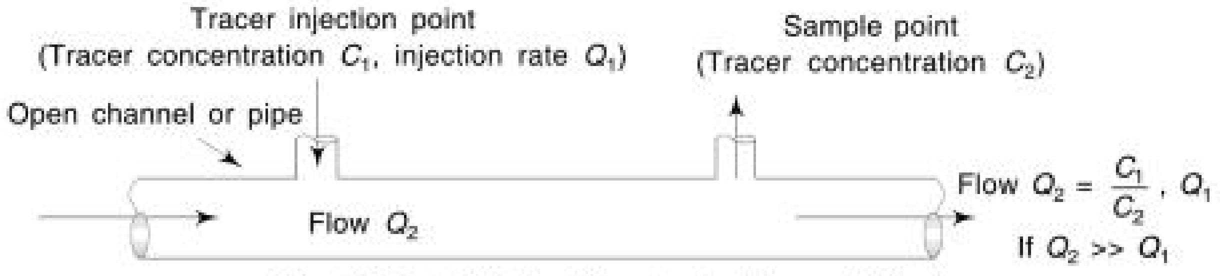

Fig. 11.29 *Dilution Gauging by Tracer Method*

Laboratory Calibration Methods The laboratory calibration methods use (a) master meter method, (b) volumetric method, (c) gravimetric method, and (d) pipe prover method.

Master Meter Method A meter of known accuracy is used as a calibration standard in this method. The meter to be calibrated and the master meter are connected in series and are therefore subject to the same flow regime. It must be borne in mind that to ensure consistent accurate calibration the master meter itself must be subject to periodic recalibration.

Gravimetric Method In this method, gas is diverted via the meter under test into gas-collecting vessel over a measured period of time. By weighing the collecting vessel before diversion and again after diversion the difference will be due to the enclosed gas, and flow can be determined. This flow can then be compared with that measured by the flowmeter.

11.7 SELECTION OF FLOWMETERS

The variety of choices facing an instrument engineer confronted with a flow measurement application is vast. The orientation table shown in Table 11.1 lists over 16 different categories of flowmeters. Therefore, an instrument engineer faces a confusing list of different type of flowmeters for deciding on a particular type for specific applications. Also, each type has its advantages and disadvantages and no one type combines all the features and all the advantages.

The meter selection for a particular application can be done as per the following steps:

(i) First, by identifying the meters which are technically capable of performing the required measurement and are available in acceptable materials of construction. Second, by making the best choice from those available.

(ii) A list should be made of the key parameters which the meter must be capable of accommodating.

(iii) By comparing these requirements with the information given in Tables 11.1 and 11.2, a first pass elimination of technically unsuitable meters can be made.

(iv) The list can then be further refined by a more detailed consideration of the applicational requirements against the 'Features Summary' at the start of each appropriate meter section.

(v) In order to cover special features such as reverse flow, pulsating flow, response time, and so on, it is necessary to study the individual meter specifications in detail and/or obtain the manufacturer's comments and advice.

Although the above steps will eliminate technically unsuitable meters, it does not necessarily follow that the available meters will be technically suitable for the application. The meter may possess the individual features required, but it may not be possible to find a combination of all the desired features in one meter.

The length of the list of technically suitable meters will depend on the complexity of the application. On an extreme application such as a highly corrosive, non-conductive liquid with large solid content, the list will probably consist of one meter at most (cross-correlation meter). On a straightforward clean water application, the list will consist of nearly all the flowmeters listed in the Orientation Table 11.1.

In order to make the subsequent selection, an instrument engineer should consider the reasons (parameters) for measuring the flow, such as accuracy, repeatability, safety, installation cost, or maintenance. The key requirements should be identified and a weighting applied to them. For example, is high accuracy the most important requirement, or is long term repeatability, low installation cost, or easy maintenance? It is important that these parameters or requirements are objectively specified. These parameters are briefly described below.

2. Velocity head is defined as the vertical distances which a column of the flowing liquid would rise in an open-end tube as a result of the static pressure.
3. Differential flowmeters exhibit a linear relationship between head and flow rate.
4. The eccentric orifice plate is used where liquid fluid contains a relatively high percentage of dissolved gases.
5. Dall tubes are generally considered for measuring flow of hot feed water.
6. Pitot tubes are used mainly for the measurement of fluid velocity.
7. Weirs and flumes are used to measure flow rates in open channels.
8. Rotameter is good in pulsating services.
9. Operating principle of cylinder and piston type flowmeter is similar to rotameters.
10. The swirlmeter operates on the phenomenon known as vortex shedding.
11. Fluidic flowmeters operate on the principle of coanda effect.
12. At low flow rates, the accuracy of rotating vane flowmeters increases.
13. Lobed impeller flowmeter requires frequent maintenance of rotating parts.

REVIEW QUESTIONS

1. (a) Name three types of rate of flowmeters.

   (b) Explain the principle of operation of one of them.
2. (a) Describe with neat sketches the principle of operation of—

   (i) an orifice plate, and (ii) venturi tube;

   as used in fluid flow measurement.

   (b) What are their relative advantages and disadvantages?
3. Describe with neat sketches, the construction and working principle of the following types of flowmeters.

   (i) positive displacement meter (ii) variable area meter

   (iii) vortex meter.
4. Discuss the advantages and disadvantages of the following restriction devices—

   (i) nozzle, (ii) piot tube, (iii) elbow tap, (iv) annular tube, and (v) dall tube.
5. What is a Reynold's number? On what factor does it depend?
6. (a) Describe with neat sketches, the construction and working of a rotameter.

   (b) What are its advantages and disadvantages?
7. (a) Discuss, with neat sketch, any type of flowmeter used to measure flow of highly corrosive liquids involving measurement of erosive slurries.

   (b) Discuss its advantages and disadvantages also.
8. Describe any type of flowmeter effectively used in aerospace and airborne applications for energy-fuel and cryogenic flow measurements.
9. Explain with neat sketch the working of a flowmeter used for measuring unsteady flow of gases.
10. Describe the working of a swirlmeter with its advantages and disadvantages.

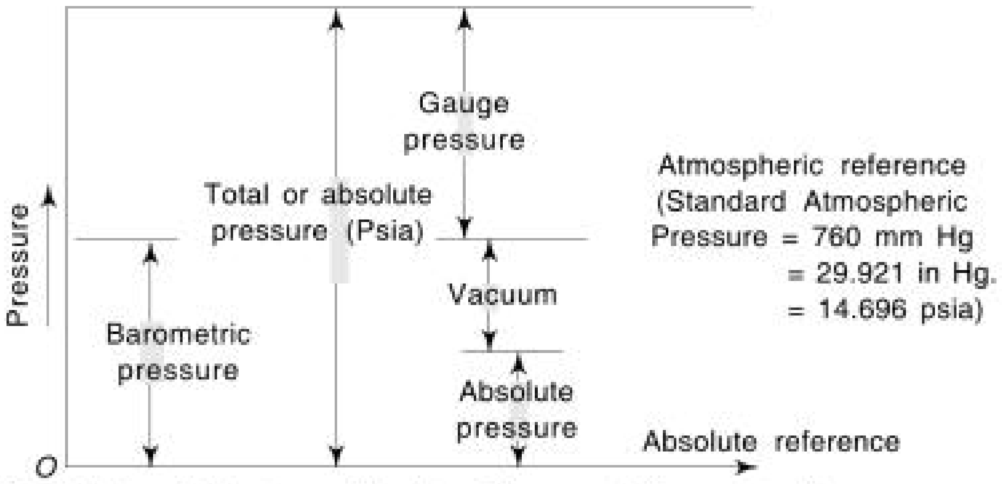

Fig. 12.1 *Relationship between Absolute, Gauge and Barometric Pressures*

The relationship between absolute, gauge and barometric pressures are illustrated in Fig. 12.1.

(d) Static Pressure and Velocity Pressure When the fluid is in equilibrium, the pressure at a particular point is identical in all directions and independent of orientation. This is called "static pressure".

Velocity pressure is the difference between the total pressure and static pressure:

Velocity pressure = Total pressure – Static pressure

12.3 METHODS OF PRESSURE MEASUREMENT

Most pressure instruments measure a difference between two pressures, one usually being that of the atmosphere. The different methods of pressure measurement are listed below.

(i) Manometer method.
(ii) Elastic pressure transducers.
(iii) Pressure measurement by measuring vacuum.
(iv) Pressure measurement by balancing the force produced on a known area by a measured force.
(v) Electrical pressure transducers.

12.4 MANOMETERS

The manometer is the simplest measuring instrument used for gauge pressure (low-range pressure) measurements, by balancing the pressure against the weight of a column of liquid. The action of all manometers depends on the effect of pressure exerted by a fluid at a depth. The different types of manometers are discussed below.

12.4.1 U-tube Manometer

The U-tube is the simplest form of manometer and is used for experimental work in laboratories. By suitable choice of liquids, a wide range of pressure can be recorded.

tube is fixed and is open for the application of the pressure which is to be measured. The tube is soldered or welded to a socket at the base, through which pressure connection is made. Figures 12.8(a) and (b) show the schematic arrangement of a complete Bourdon tube gauge.

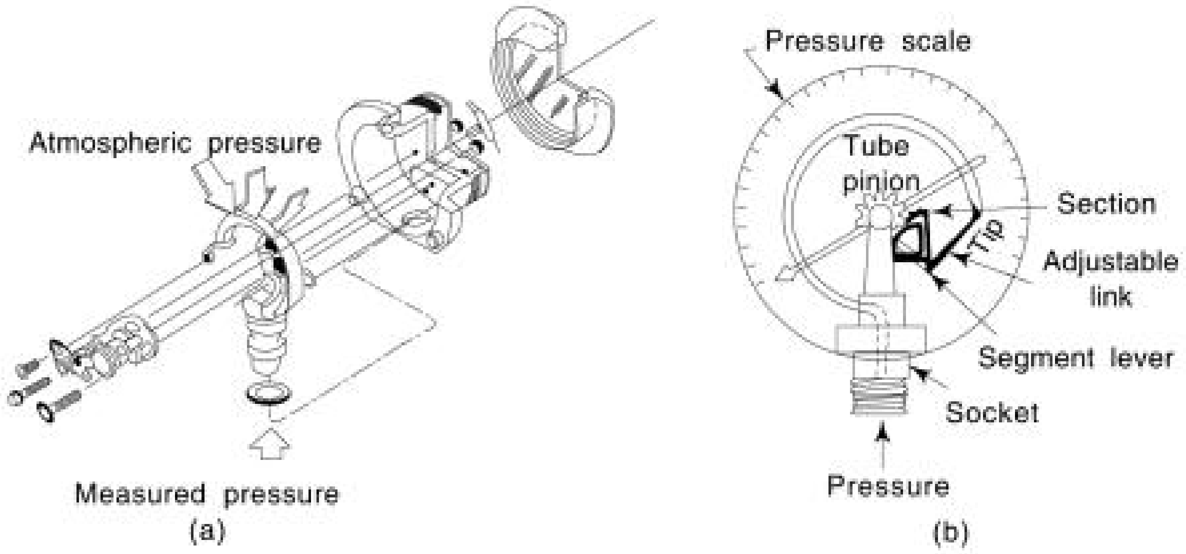

Fig. 12.8 (a) *Pressure Gauge (Exploded View)*
(b) *How a C-type Bourdon Tube Indicates Pressure*

As the fluid under pressure enters the Bourdon tube, it tries to change the section of the tube from oval to circular, and this tends to straighten out the tube. The resulting movement of the free end of the tube causes the pointer to move over the scale. The tip of the Bourdon tube is connected to a segmental lever through an adjustable length link. The lever length also may be adjustable. The segmental lever end on the segment side is provided with a rack which meshes to a suitable pinion mounted on a spindle. The segmental lever is suitably pivoted and the spindle holds the pointer, as shown in Fig. 12.8(b). A hairspring is sometimes used to fasten the spindle to the frame of the instrument to provide the necessary tension for proper meshing of the gear teeth, thereby freeing the system from backlash. Any error due to friction in the spindle bearing is known as "lost motion".

Bourdon tubes are made of a number of materials, depending upon the fluid and the pressure for which they are used, such as phosphor bronze, alloy steel, stainless steel, "Monel" metal, and beryllium copper. For adequate reliability, the materials for Bourdon tubes must have good elastic or spring characteristics. Bourdon tubes are generally made in three shapes: (i) C-type, (ii) Helical type, and (iii) Spiral type.

Adjustments Basically there are two types of adjustments of the Bourdon tube:

(a) Multiplication Adjustment Because of compound stresses developed in the Bourdon tube, actual travel is non-linear in nature. However, for a small travel of the tip this can be considered to be linear and parallel to the axis of the link. The small linear tip movement is matched with a rotational pointer movement. This is known as 'multiplication' and can be adjusted by adjusting the length of the lever. A shorter lever gives larger rotation for the same amount of tip travel.

The compression of gas in the closed capillary tube makes the pressure of the trapped gas higher than the measured pressure. This pressure difference causes a difference in the mercury levels in the two tubes. The difference in height is used to calculate the pressure.

The volume of the bulb can be made quite large and the zero reference line on the closed capillary tube can be placed near the top of the tube. Thus, a large volume of gas can be compressed into a very small volume. This compression multiplies the pressure many times. The pressure can be calculated by using the following equation:

$$P = KH\,H_0\,(1 - KH) \tag{12.2}$$

where P = measured pressure
K = a constant, determined by the geometry of the gauge
H = difference in heights of the two mercury columns
H_0 = height of the top of the closed capillary tube above the line marked on the tube.

The McLeod gauge is a very accurate pressure-measuring device and often serves as a standard for calibrating other low-pressure gauges. It can be designed to measure pressures as low as 0.05 microns (0.00005 torr).

12.6.3 Thermal-conductivity Gauge

Thermal-conductivity gauges measure pressure by measuring the changes in the ability of a gas to conduct heat. The ability of a material to carry heat by conduction is called "thermal conductivity". The conductivity of a gas does not change when the pressure changes, until the pressure drops below about one torr. As the pressure continues to drop, the conductivity of the gas decreases and the gas loses its ability to conduct heat. Thus, at low pressure, the conductivity of a gas has a direct relationship to its pressure. The relationship between changes in conductivity and changes in pressure work over a pressure range from about 10^{-4} torr upto about 10^{-2} torr. It is used for the absolute pressure (very low pressure) measurement.

Basic Operating Principles A pressure gauge based on changes in thermal conductivity is made by enclosing a wire filament in a chamber connected to the pressure source. When voltage is applied to the filament, electricity flows, making it hot. The rising temperature increases the resistance of the filament. The filament then reaches an 'equlibrium temperature', the temperature at which heat is produced in the filament as fast as it is removed. Heat is removed by both radiation and conduction. Convection is so slight that it can be ignored.

The voltage applied to the filament is held constant and any change in pressure causes a change in conductivity of the gas surrounding the filament. The change in conductivity changes the equilibrium temperature of the filament, which in turn causes the change in the resistance. Therefore, the change in resistance is used to indicate the pressure change.

An increase in conductivity (due to an increase in pressure) increases the flow of heat away from the filament, decreasing the temperature of the filaments. A decrease in conductivity (due to decrease in pressure) increases the filament temperature.

which in turn changes the position of the bell. The travel of the bell is proportional to the differential pressure. Figure 12.20(b) shows the diagram of a thin wall bell type pressure gauge.

In this type of instrument the range is determined by the modulus of elasticity of the spring and the density of the sealing liquid. For low ranges upto a few inches of water an organic liquid is used as a seal. For higher ranges, mercury is used.

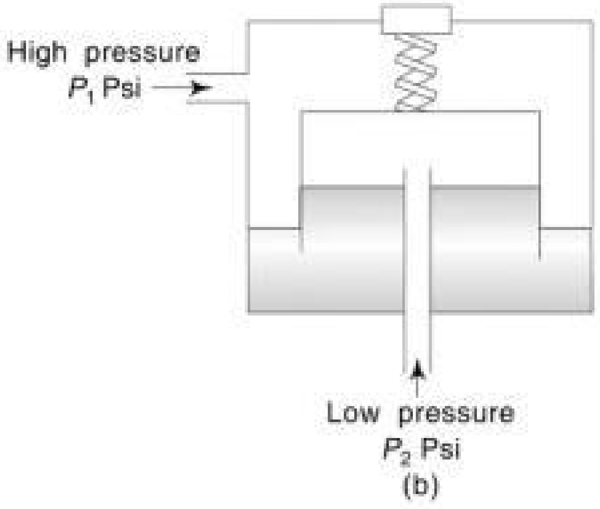

Fig. 12.20(b) *Thin Wall Bell Gauge*

12.8 ELECTRICAL PRESSURE TRANSDUCERS

In general, "a transducer is a device which converts one form of energy into another form of energy." However, in the field of electrical instrumentation, "a transducer is defined as a device which converts a physical quantity, a physical condition, or mechanical output into an electrical signal".

Most of the methods of converting mechanical output into an electrical signal work equally well for the bellows, the diaphragm and the Bourdon tube.

In this conversion, a mechanical motion is first converted into a change in electrical resistance and then the change in resistance is converted into a change in electrical current or voltage.

Generally, an electrical pressure transducer consists of three elements:

(i) Pressure sensing element such as a bellow, a diaphragm or a Bourdon tube.
(ii) Primary conversion element, e.g. resistance or a voltage.
(iii) Secondary conversion element.

Following are the different types of commonly used electrical pressure transducers.

12.8.1 Strain Gauge Pressure Transducer

Strain gauge is a passive type resistance pressure transducer whose electrical resistance changes when it is stretched or compressed. It can be attached to a pressure sensing diaphragm.

Basic Principle The strain gauge is a fine wire which changes its resistance when mechanically strained, due to physical effects. A strain gauge may be attached to the diaphragm so that when the diaphragm flexes due to the process pressure applied on it, the strain gauge stretches or compresses. This deformation of the strain gauge causes the variation in its length and cross-sectional area due to which its resistance also changes, as shown in Fig. 12.21(a).

The resistance change of a strain gauge is usually converted into voltage by connecting one, two, or four similar gauges, as of a wheatstone bridge (known as strain gauge bridge), and applying excitation to the bridge. The bridge output voltage is then a measure of the pressure sensed by the strain gauges.

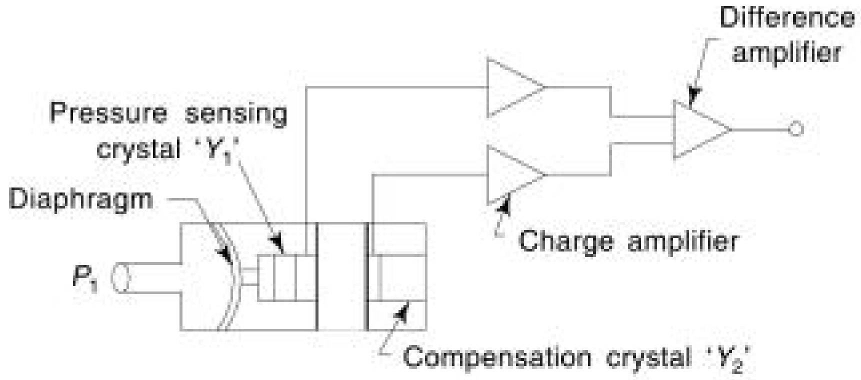

Fig. 12.26 *Piezoelectric Pressure Transducer*

barium titanate sintered powder, crystal of quartz, tourmaline, and Rochelle salts. Figure 12.26 shows a piezoelectric pressure transducer.

Construction and Working It consists of a diaphragm by which pressure is transmitted to the piezoelectric crystal Y_1. This crystal generates an electrical signal which is amplified by a charge amplifier. A second piezoelectric crystal Y_2 is included to compensate for any acceleration of the device during use. This compensation is needed because rapid acceleration of the transducer creates additional pressure on the piezoelectric crystal. Vibration is a major source of high, rapidly changing acceleration.

Signals from the compensating crystal, are amplified by a second charge amplifier. A different amplifier is used which substracts pressure alone; all effects of acceleration are removed.

Piezoelectric pressure transducers are used to measure very high pressures that change very rapidly. For example, the pressure inside the cylinder of a gasoline engine changes very rapidly from less than atmospheric pressure to many thousands of pounds per square inch. Similar pressure changes occur in compressors, rocket motors, etc. It is impossible for ordinary pressure transducers to measure such great pressure changes over such short time periods. They do not respond fast enough. But piezoelectric materials produce an electrical voltage when they are squeezed suddenly. The voltage disappears when the pressure stops changing.

Piezoelectric pressure transducers may be used to measure pressures over ranges upto 0–50,000 psi. However, piezoelectric transducers cannot measure steady pressures. They respond only to changing pressures.

Advantages The advantages of piezoelectric pressure transducers are:

(i) The transducer needs no external power and is therefore self-generating (active type).

(ii) It has a very good high-frequency response.

Disadvantages The disadvantages of piezoelectric pressure transducers are:

(i) This type of transducer cannot measure static pressures.

(ii) The output of the transducer is affected by changes in temperature. Therefore, temperature-compensating devices have to be used.

Ranges of low-pressure instruments are given in Table 12.2.

12.11.2 Care of the Instrument

The following steps should be taken for pressure-measuring instruments:

(i) Liquid-filled manometers must be levelled, the liquid and the chambers must be kept at a reasonably constant temperature, and errors must not be introduced in the connecting pipes. Proper allowance must be made for the pressure due to liquids in the pipes where liquid enters the manometer.

(ii) Owing to the very large variation in design and construction of instruments, it is always necessary to consult the manufacturer's recommendations for installation, servicing and maintenance.

(iii) All pressure gauges should be mounted correctly, protected from heat, corrosion, and vibration.

(iv) The zero of the instrument should be checked daily, or weekly, depending upon the variation found, and it should be corrected if this is found necessary.

(v) The calibration should be checked every 3,6 or 12 months, depending upon the use and the accuracy expected.

(vi) If the instrument contains mercury, the mercury chamber should be checked every six months and the mercury should be cleaned or replaced if necessary.

12.12 TROUBLESHOOTING

Troubleshooting helps in quickly finding instrument failure. The first important step in troubleshooting is to observe the instrument in operation, and write down its symptoms. The instrument manufacturer's troubleshooting chart should be used as a guide for observing key symptoms. Table 12.3 shows a typical troubleshooting chart for locating a problem in a faulty pressure transmitter. Table 12.4 is an orientation table for pressure detectors.

Table 12.3 *Troubleshooting Chart*

Symptom	*Possible Causes*	*Corrective Action*
Low output or zero output.	Power supply loop wiring.	Check output of power supply. Check for shorts and multiple ground Check polarity of connections. Check loop impedance.
	Pressure piping.	Check that pressure connection is correct. Check for leaks or blockage. Check that blocking valves are fully open. Check for entrapped gas in liquid lines and for liquid in dry lines. Check for sediment in transmitter process flanges.
	Transmitter electronic connections.	Check for shorts in sensor leads. Make sure bayonet connectors are clean and check the sensor connections.
	Transmiter electronic failure.	Determine faulty amplifier assembly by trying spare assembly. Replace faulty amplifier assembly.

(*Contd*)

13.3 TEMPERATURE SCALES

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

(i) the lower fixed point, or ice-point

(ii) the upper fixed point, or steam-point

The *lower fixed point, or ice-point*, is the temperature of ice, prepared from distilled water, when melting under a pressure of 760 mm of mercury. The *upper fixed point, or steam-point* is the temperature of steam from pure distilled water boiling under a pressure of 760 mm of mercury. The boiling point of water varies greatly with the applied pressure. Thus, it is very important to note the pressure at which the water is boiling.

The temperature interval between the ice-point and steam-point is known as the "fundamental interval". In order to graduate a thermometer between these fixed points, the temperature interval between the points is divided into a number of equal parts. Different temperature scales are discribed below:

13.3.1 Fahrenheit and Centigrade (Celsius) Temperature Scales

The fahrenheit scale, abbreviated °F, was introduced in about 1709 by a German philosopher Fahrenheit, and the centigrade (Celsius) scale, abbreviated °C, was introduced in about 1742 by a Swedish astronomer and professor, Celsius. These scales are based on the fact that the melting of ice and the boiling of water occur at certain fixed temperatures, at standard atmospheric pressure (14.7 psi).

On the fahrenheit temperature scale, the melting point of ice is designated at 32°F and the boiling point at 212°F. On the centigrade temperature scale, the melting point of ice is designated at 0°C and the boiling point at 100°C. Between the two fixed points, the fahrenheit scale is divided into 180 equal divisions and the centigrade scale into 100 equal divisions. Since both scales are linear, temperatures can be easily converted from one to the other, using the following equation.

$$\frac{^\circ C}{100} = \frac{^\circ F - 32}{180} \qquad (13.1)$$

13.3.2 Kelvin and Rankine Temperature Scales

The Kelvin scale, abbreviated as °K, was introduced in about 1848, by Lord Kelvin 1824–1927. On the kelvin temperature scale, the ice-point is 273.15°K and the steam-point 373.15°K. The kelvin scale, like the centigrade scale, is also divided into 100 equal divisions. The centigrade (°C) can be converted into Kelvin (°K) by using the equation:

$$^\circ K = ^\circ C + 273.15 \qquad (13.2)$$

The rankine scale is abbreviated as °R. On the rankine scale, the ice-point is 491.7°R and the steam point is 671.7°R. The rankine scale, like the fahrenheit scale, is also divided into 180 equal divisions. Temperature in fahrenheit (°F) can be converted into rankine (°R) by using the equation:

$$^\circ R = ^\circ F + 459.69 \qquad (13.3)$$

The liquid-in-glass thermometers have got certain disadvantages also. They are fragile and not easily adapted to automatic recording or transmission of temperature data. This limits their use in modern industries. They can be difficult to read also. In the mercury-in-glass thermometer, a large error may be introduced by changes in the size of the bulb due to ageing.

The industrial mercury-in-glass thermometer is used in applications such as open tanks containing liquids, cooking kettles, certain moltenmetal baths, steam lines, pipe lines for fluid flow, and air ducts. It should not be employed when rapidly fluctuating temperatures are to be measured with high accuracy.

13.5.3 Liquid-in-metal Thermometer

The distinct disadvantages of liquid-in-glass thermometers are overcome in liquid-in-metal thermometers. A liquid-in-metal thermometer is shown in Fig. 13.7 in which mercury has been used as liquid and the metal is steel. This mercury-in-steel thermometer works on exactly the same principle as the liquid-in-glass thermometer. The glass bulb is replaced by a steel bulb and the glass capillary tube by one of stainless steel. Mercury is used as liquid in the system. As mercury in the system is not visible, a Bourdon tube is used to measure the change in its volume. The Bourdon tube, the bulb and the capillary tube are completely filled with mercury, usually at a higher pressure.

When the temperature to be measured rises, the mercury in the bulb expands more than the bulb so that some mercury is driven through the capillary tube into the Bourdon tube. As the temperature continues to rise, increasing amounts of mercury will be driven into the Bourdon tube, causing it to bend. One end of the Bourdon tube is fixed, while the motion of the other end is communicated to the pointer which moves on a calibrated temperature scale.

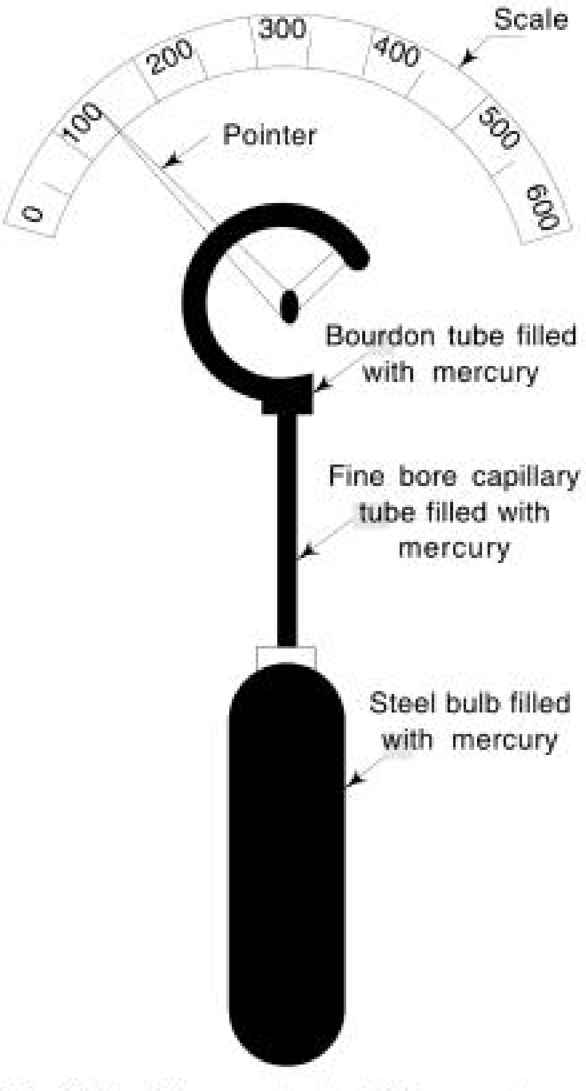

Fig. 13.7 *Mercury-in-steel Thermometer*

The Bourdon tube and thermometer bulb may have a variety of forms, depending upon the use to which they are put. The thermometer bulb is also placed in a protective pocket where the gas or liquid whose temperature is being measured, is at a pressure other than atmospheric. In this case the pocket prevents the bulb being subjected to this pressure and also enables the bulb to be changed without

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