# 1

# *Basic Principles of Measurement*

## 1.1. What is Measurement ?

Measurement is the act, or the result, of a quantitative comparison between a predetermined standard and an unknown magnitude. It is essential that the procedure and apparatus employed for obtaining the comparison must be provable, *i.e.* it must be caused to prove its ability to measure reliably. The procedure for this is called calibration. In order that the results of measurements be meaningful and followed by all, the standard which is used for comparison must be accurately known and commonly accepted. Further the apparatus used and the method used for comparison must be provable. Measurements cover a wide range starting from detection/sensing, data manipulation, transmission, acquisition, control and analysis of data. The quantities involved in measurement could be physical, mechanical, electrical, optical, chemical, etc. The advancements in various fields of science are to a great extent dependent on the reliability of measurement data.

## 1.2. Aims of Measurement

In the field of engineering design, research and development programme, the measurements and correct interpretation thereof are the source of great importance and necessary information. Secondly, in the process industries and power plants and several other production industries, the aim is to achieve quality of product and have maximum efficiency. For this purpose and for the maintenance of proper operation, measurements, *i.e.* instrumentation plays a vital role. Thirdly the whole area of automation or automatic controls is based on measurements. The very concept of control is based on the comparison of the actual condition (known by measurement) and the desired performance (set value). The controlling portion of the system must know magnitude and direction of error to react intelligently. The exactness of error depends on the precision and accuracy of measurements made.

With the increasing complexity of the systems, the greatest advances during the past few years have occurred in the general area of "dynamic" measurements. The need of measurement of transient phenomena, whose complete history must be recorded in milli or micro-seconds, has been felt and methods developed for the same. It may be stressed here that for measurement to be of greatest usefulness, all factors influencing the measuring process must be understood.

## 1.3. Measurement in Design

Basically, there are three distinct methods or approaches essential to determine the complete solutions to complex problem in mechanical design. Realising the importance of use of measurements as design tool, some space is devoted here to these three methods, *viz.*, (*a*) the empirical method, (*b*) the rational method, (*c*) the experimental method.

In empirical method, use is made of the knowledge of satisfactory previous performance, either personally observed or generally recognised as "good practice". The results of such observations are available in the form of "rule of thumb" in handbooks etc.

In the rational approach, each design step is based on accepted scientific theory, knowledge or law.

In most of the applications both these approaches are not able to yield satisfactory solution and in such cases, the experimental design and development design has to be considered as the only solution and practical way of getting the job done. In this third approach, the component is designed by trial and error based on existing knowledge and the designed component is put on the job; the trials made with intelligence and the error wisely interpreted.

## 1.4. Classification of Methods of Measurements

Most of the mechanical measurements can be classified as (*a*) mechanics type or self-operated type, and (*b*) power type. The mechanics type of mechanical measurements are commonly applied to experimental or developmental programmes and the power type are generally used for monitoring of operational measurement in control system. The self-operated instrument like mercury in glass thermometer, drives its power wholly from the thermal expansion of mercury. The power-operated instruments require a source of auxiliary power, such as compressed air, electric power, hydraulic supply or a mechanical source of power.

Another classification of instruments can be according to their arrangement, *i.e.* self-contained or remote indicating type. In the self-contained instruments all parts of the instrument from primary element to indicating element are contained in one physical assembly. In the remote indicating instruments, the primary element is located hundreds of feet from the secondary indicating instrument. Usually remote indicating instruments are used, as now-a-days trend is for central control rooms where all important indications are displayed.

Sometimes instruments could also be classified as automatic instruments or manual instruments. In automatic instruments the services of an operator are not required in fulfilling its function whereas the manual instruments require. Usually only automatic instruments are used.

There are several methods of classifications depending on the aspects considered. The various ways are (*a*) Primary, secondary, and tertiary measurements. (*b*) Mechanical, electrical and electronic instruments. (*c*) Absolute and secondary instruments. (*d*) Analogue and digital instruments.

### (*a*) *Primary, Secondary and Tertiary Measurements*

1. **Primary Measurements.** *A primary measurement* is one that can be made by direct observation without involving any conversion of the measured quantity. In this case, the change in the measured quantity stimulates a set of the observer's nerve endings, so that the observer can see or sense the change directly. Typical examples of primary measurements are (*i*) the matching of two lengths, (*ii*) the matching of two colours.

It is noted that the most uniform agreement between different observers about magnitude of a measurement is obtained when *'sight'* is used as the sense for transmitting to the observer's brain. Also, there is greater agreement between observers when the measurement is transmitted to the brain in the form of a length or a change in length. When the measurement is transmitted to the brain in the form of colour variation, light intensity variation, or by any of the other senses, the agreement between observers about the size of measurement is very poor. Therefore, majority of the measurements are transmitted to the observer's brain in the form of a length or a change in length. For this purpose a measurement which is not a length or change in length is converted into change in length and the measurement is made by means of a pointer moving over a scale with units of measurements marked at length intervals on the scale.

**2. Secondary Measurements.** A *secondary measurement* involves only one conversion to be done on the quantity under measurement. A secondary measurement requires,

(*i*) an instrument which translates changes in desired parameter into translatory motion.

(*ii*) a standard which is calibrated in length units equivalent to known changes in designed parameter.

**3. Tertiary Measurements.** A *tertiary measurement* involves two conversions. A typical example of such a measurement is the measurement of temperature of an object by thermocouple. The primary signal (temperature of object) is transmitted to a thermocouple which generates a voltage which is a function of the temperature. Therefore, first translation is temperature to voltage. The voltage, in turn, is applied to a voltmeter through a pair of wires. The second conversion is then voltage into length. The tertiary signal is transmitted to the observer's brain.

(*b*) *Mechanical, Electrical and Electronic Instruments*

**1. Mechanical Instruments.** These instruments have moving parts that are rigid, heavy and bulky and consequently have a large mass. Mass presents inertia problems and hence these instruments cannot faithfully follow the rapid changes which are involved in dynamic measurements. These instruments are very reliable for static and stable conditions. But they are unable to respond rapidly to measurements of dynamic and transient conditions.

**2. Electrical Instruments.** Electrical methods of indicating the output of detectors are more rapid than that of mechanical methods. It is unfortunate that an electrical system normally depends upon a mechanical meter movement as an indicating device. This mechanical movement has some inertia and therefore these instruments have a poor frequency response.

**3. Electronic Instruments.** Most of the present day scientific and industrial measurements require very fast responses. These instruments use semi-conductor devices. Since in electronic devices, the only movement involved is that of electrons, the response time is extremely small on account of very small inertia of electrons.

Another advantage of using electronic devices is that very weak signals can be detected by using pre-amplifiers and amplifiers.

(*c*) *Absolute Instruments, and Secondary Instruments*

**1. Absolute Instruments.** These instruments give the magnitude of the quantity under measurement in terms of physical constants of the instrument. The examples of this class of instruments are Tangent Galvanometer and Rayleigh's current balance.

**2. Secondary Instruments.** These instruments are so constructed that the quantity being measured can only be measured by observing the output indicated by the instrument. These instruments are calibrated by comparison with an absolute instrument or another secondary instrument which has already been calibrated against an absolute instrument.

(*d*) *Analogue and Digital Instruments*

Indications which vary in a *continuous* fashion and take on an infinity of values in any given range are called analogue indications and the instruments which handle these signals are called *analogue* instruments.

Indications which vary in *discrete* steps and thus take up only finite different values in a given range are called digital signals and the instruments which handle such signals are called *digital* instruments.

## 1.5. Fundamental Methods of Measurement

There are two basic methods of measurement :

(*i*) Direct comparison,

(*ii*) Indirect comparison.

There are two different ways of looking at this classification. In the field of mechanical measurements, this classification is seen in the following way : In direct comparison the parameter to be measured is directly compared with either a primary or a secondary standard. In the indirect comparison the comparison is done with a standard through use of a calibrated system. Direct comparison is quite commonly used for length measurements. Generally the direct comparison is not always the most accurate or the best; it is not sensitive enough also. The human senses are not equipped to make direct comparisons of all quantities with equal facility.

As our senses enable to make only rough comparisons with direct comparisons, we need assistance from some form of calibrated measuring system to achieve greater accuracy. The indirect comparison methods are very essential in industries. All such methods employ a system which senses, converts, and finally presents an analogous output proportional to the input in the form of a displacement on a scale or chart. Processing of the analogous signal may take many forms, such as amplification to increase the amplitude or filtering of the extraneous input signals in order to extract the desired information, or superimposing the primary signals with a radio-frequency signal for remote recording. All these require the use of electrical methods. For dynamic mechanical measurements also the transducers are used which convert the mechanical input into an analogous electrical form for processing.

In process industries the direct and indirect measurement has got different sense. All the physical dimensions are generally measured by direct methods. In the direct measurements, the meaning of the measurement and the purpose of the processing operation are identical. In the indirect measurements the meaning of the measurement and the purpose of the processing are not the same but are related to each other. Indirect methods for measurements are used in those cases where the desired parameter to be measured is difficult to be measured directly, but it has got some correlation with some other parameter which can be measured easily, *e.g.,* bacteria elimination in milk is directly dependent upon its temperature. Thus the bacteria elimination can be measured indirectly by measuring the temperature of the milk. In indirect measurements an empirical relation is generally established between the measurement actually made and the results that are desired. A point about direct and indirect methods may be noted that if the primary purpose of making a measurement is to determine quality of a product, then, one should measure that quality directly, but, however, if the direct measurement is not possible, then, only indirect measurement should be restored to.

## 1.6. Factors in Selection of Measuring Instruments

Whenever anybody is asked to measure any quantity, the following five points which are completely fundamental in the philosophy of measurement should always be born in the mind. All these points in addition to a few more are very essential for the proper selection of a correct instrument for any application.

(*a*) How accurate is the measurement to be made, *i.e.* the accuracy expected from the instrument ?

(*b*) When are the final data required, *i.e.* at the time of taking the measurement, or later on ?

(*c*) The cost criterion, *i.e.* how expensive can the measuring process be ?

(*d*) In what form the data should be displayed, *i.e.* indicating, recording, integrating or photograph etc. ?

(*e*) Whether quantity to be measured has constant value or is it a time variant ? If time variant, then whether variation is linear, parabolic or of some other type ? In other words, one should have the thorough knowledge of the complete process also. All these points are interrelated and the answer to one has repercussion on the other. We will now consider their precise implications and the reasons for their importance, keeping in mind that the correct answer to a particular question will be dependent on the answers given to one or more of the others.

It may be stressed here that accuracy, *i.e.* the probable departure from an absolutely correct value of the quantity being measured, is the most fundamental and key question. Generally, "How accurate a measurement should be" determines the type of instrument to be selected. It is very easy to demand a high accuracy in a particular measurement but it is often difficult to achieve. If high accuracy is insisted upon, then highly sophisticated and specialised instruments, having special ancilliaries to compensate for ambient conditions, requiring periodic calibrations etc., have to be used. This may lead to increased expenses, perhaps to such an extent that it is considerably more than the expected cost of measurement process. In view of the above the following most significant and fundamental rule, which is perhaps the most important rule in measurement must always be kept in mind.

"Never demand an accuracy of measurement higher than that which is really needed, and never forget that each degree of accuracy, if demanded, is likely to have a disproportionate effect on the complexity and cost of the measuring apparatus."

Although no general rules can be laid down for the accuracy to be demanded in particular circumstances, but if a particular measurement is one of a set of several others which have to be combined to produce a final result, and if they are mutually independent, then nothing much will be gained by straining one particular factor to be measured to a very high accuracy, if for some reason or other any one factor out of all can't be measured to that high accuracy.

In the measurement of time variant quantities, the manner in which the quantity to be measured changes has a profound effect on the type of measuring instrument to be used. This is because the physical characteristics of the measuring device determine the amount of interaction which takes place between the measured quantity and the instrument. Thus the physical characteristics of the measuring device must always be taken into account. Actually this is the fact which is too easily overlooked in the use of instruments which depend for their action on the alteration of some physical property by the condition being measured. The importance of this point can be realised when it is made clear that many of the most precise, expensive and elaborate measuring instruments owe their cost and complexity solely to the means adopted to eliminate, or at least reduce, interaction between the instrument and the physical state it is used to measure.

The point which is being stressed here would become obvious from the following examples :

(*a*) The quantities which can be transduced into voltage signals are measured either by conventional moving coil voltmeter or by a potentiometer. It is well known fact that potentiometer is more accurate than moving-coil voltmeter. The reason is that the conventional moving-coil voltmeter draws a current in order to deflect its pointer and in doing so some voltage is dropped across its own coil. Hence the potential across the terminals is not quite the same as it was before the instrument was connected to them. The reading noted, therefore, is in error, although it is very minute. On the other hand, a potentiometer draws no current provided it is correctly nulled.

(*b*) For temperature measurement, usually hot wells or bulbs are provided around the sensing device in order to protect them. These possess their own heat capacity and absorb heat in order to operate. If the temperature being measured is that of an object having relatively small heat capacity, its temperature will fall whilst the instrument element is becoming heated, so the final temperature registered will not be that of the object alone.

(*c*) The flow in pipes is usually measured by an orifice plate, by measuring the differential pressure across it. Actually the presence of the orifice alters the flow pattern in the pipe, consequently the flow rate shown by the meter is not the same as it was before the orifice plate was installed.

## 1.7. Measurement Systems

There are three or four phases in most of the measuring systems, each phase being made up of a distinct component or grouping of components which perform required and definite steps in measurement *viz.*, (*i*) primary sensing device, (*ii*) transducer, (*iii*) intermediate modifying stage, (*iv*) terminating stage, *i.e.* secondary indicating instrument.

Sometimes primary sensing device and the transducers are in the form of one unit only. The sensing device must be sensitive to the input quantity (*i.e.* variable to be measured) so that it can sense or detect it, and at the same time sensing device must be insensitive to other variables. In other words the sensing device must be selective, as far as possible; of course, it can't be made completely selective. After sensing the desired input, it provides an analogous output with the help of transducers. Actually the transducer converts the input signal into another type of quantity which is more useful and is, of course proportional to the input quantity. The various sensing devices and transducers have been dealt with in details in separate chapters. However, a brief mention of different types of basic detectors-transducers is made here. These can be of mechanical type in which category they may utilise contacting spindle, spring mass, elastic devices such as Bourdon tube, proving ring etc. The hydraulic-pneumatic type of detectors consist of buoyant float, orifice, venturi, vane, propeller etc. The optical detectors consist of photo-electric cell, photo-voltaic cell, photo-conductive cell, infrared detectors, ultra-violet detectors, photographic films and a host of others. Nowadays the electrical detectors are most commonly used and these have been developed to such an extent that they can be used for nearly all the applications. The electrical sensing elements and transducers utilise the following : contactor, resistance, capacitance, inductance, piezo-electric crystal, thermocouple, moving electrode, streaming potential and several other such devices.

The intermediate modifying stage modifies the transduced signal into a form which is suitable to be used as input to the terminating stage. It also increases the amplitude or power of the signal to the level required to drive the secondary indicating instrument. It may also perform the operations of selecting, modifying, integrating etc., as may be required. The various intermediate modifying devices can be of the following types : mechanical, hydraulic-pneumatic, optical and electrical. The mechanical devices include gearing, cranks, slides, connecting links, cams etc; the hydraulic-pneumatic devices include piping, valving, dash pots etc.; the optical devices may comprise of lenses, mirrors, light levers, filters etc.; and the electrical devices, the most commonly used devices include amplifying or attenuating systems, matching devices, filters, telemetering devices etc.

The intermediate modifying stage comprises of variable conversion stage and variable manipulation stage. The output of the primary sensing element may be a voltage, a frequency or some other electrical parameter. It may be necessary to convert this output to some other suitable form while preserving the information content of the original signal.

This function is achieved by variable conversion stage.

The function of Variable Manipulation stage is to manipulate the signal presented to it preserving the original nature of the signal.

The output of transducers contains information needed for further processing by the system and the output signal is usually a very small voltage or some other kind of electrical signal. A fundamental problem is to prevent this signal being altered or obscured by unwanted signals like noise due to an extraneous source which may interfere with main signal. Another problem is that the signal may be distorted by processing equipment. The signal after being sensed cannot be directly transmitted to the next stage without removing the interfering sources, otherwise highly distorted results will be obtained. Therefore, it is desirous to perform certain operations on the signal before it is transmitted further. These processes may be linear like amplification, attenuation, integration, differentiation, addition and subtraction. Some non-linear processes like modulation detection, sampling, filtering, chopping and clipping etc. are performed on the signal to bring it to the desired form. This is called signal conditioning. The term *signal conditioning* includes many other functions in addition to variable conversion and variable manipulation. In fact the element that follows the primary sensing element in any instrumentation system should be called *signal conditioning element.*

When the elements of an instrument are actually physically separated, it becomes necessary to transmit data from one to another. The element that performs this function is called a *Data Transmission Element* which may comprise of simple to complicated telemetry systems using radio signals.

The signal conditioning and transmission stage is commonly known as *Intermediate Modifying Stage.*

The terminating stage also called data presentation stage provides information to the observer to enable him evaluate the output with unaided eye. Visual display devices may take the form of analogue or digital indicators.

## 1.8. Input-Output Configuration of Instruments

Fig. 1.1 shows a generalised input-output configuration of a measuring system. Normally a measuring system is fed with a desired input from a sensor or transducer and output is produced according to the value of the desired input. However in some cases the output has to be modified depending on desired input and another input called modifying input. For example, mass flow is dependent on differential pressure across a nozzle but has to be modified according to change in density of medium. Thus modifying input in the form of temperature of medium (indicative of density) would

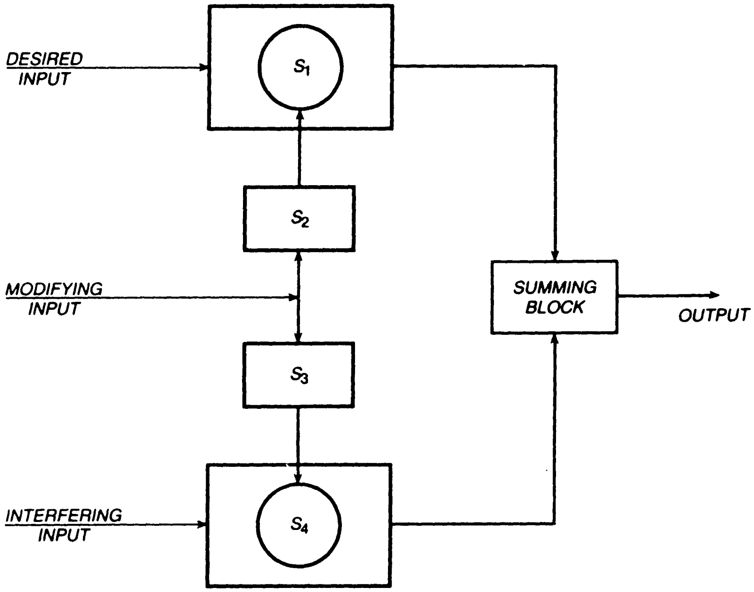


Fig. 1.1. Generalised Input-Output Configuration.

also need to be applied. In addition, there may be interfering or unwanted inputs also like noise which we desired should not affect the output.

Thus inputs to a measuring system could be of three types.

(*i*) **Desired Input.** A basic quantity for which instrument is specifically designed, and output should respond to this input. The output could be linearly proportional to input or follow a certain relationship symbolised by a mathematical operator $S_1$, defined as a transfer function, such that output = $S_1 \times$ input. In case of non-linear systems, the transfer function is represented by an algebraic or a transcendental function. If input is dynamic, then $S_1$ may be represented by differential equations.

(*ii*) **Modifying Inputs.** These cause a change in input-output relationships for desired input/interfering input. The transfer functions $S_2$ and $S_3$ represent the specific manner in which modifying input affects $S_1$ and $S_4$ respectively.

(*iii*) **Interfering Inputs.** These are unwanted signals to which the measurement system becomes unintentionally sensitive. Measuring system gives output corresponding to interfering input due to its principle of working and design. The interfering input could be generated in the system or outside due to pick up of stray signals, environmental influence, etc. Interfering input is operated upon by a transfer function $S_4$ to produce an output in a manner as the desired input is operated upon by $S_1$. The outputs from blocks $S_1$ and $S_4$ are connected to a summing block so that its output after adding the instantaneous values of $S_1$ and $S_4$ is in desired relationship with desired input.

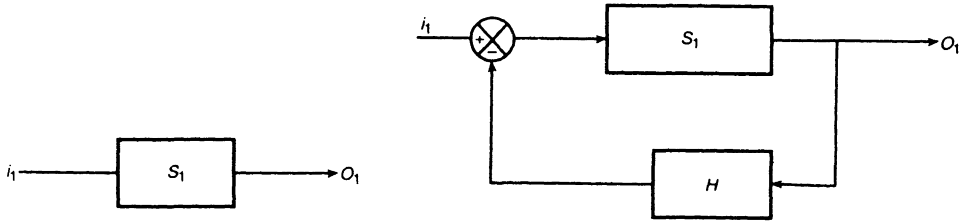
## 1.9. Correction for Interfering Inputs

Various methods are available to reduce or nullify the effects of interfering inputs.

(*a*) **Method of inherent insensitivity.** The measuring system is so designed that it is insensitive to interfering inputs but is sensitive to desired input. It is possible by making $S_4 = 0$. One example is to use a material of strain gauge having a very low resistance temperature coefficient so that the environmental temperature does not change the resistance of strain gauge and same is changed only due to change in force/stress applied on strain gauge. This method though not practical, but acts as a motivating factor in many cases to use ingenuity for elimination of effects of spurious inputs.

(*b*) **High gain feedback system.** Feedback or closed loop systems find useful applications in modern instruments to perform the assigned task automatically. It makes the system response relatively insensitive to interfering inputs.

Let us first consider an open loop or non-feedback system having input $i_1$, transfer function $S_1$ and output $O_1$, so that $O_1 = S_1 \times i_1$ [Refer Fig. 1.2 (*a*)] Now if interfering input changes $S_1$ by $\Delta S_1$ then modified output $O'_1 = (S_1 + \Delta S_1)\, i_1 = S_1 i_1 + \Delta S_1 \times i_1$. Thus change in output due to change in transfer function is $\Delta O_1 = \Delta S_1 \times i_1$ ...(1)



(*a*) Non-feedback loop system. (*b*) Closed-loop system.

Fig. 1.2.

Let us now consider a feedback or closed loop system utilising high gain feedback transfer function $H$ as shown in Fig. 1.2. ($b$). For this system

$$O_1 = \frac{S_1}{1+S_1H} i_1$$

If due to interfering signal, $S_1$ changes by $\Delta S_1$, then

$$O'_1 = \frac{S_1+\Delta S_1}{1+(S_1+\Delta S_1)H} i_1 = \left(\frac{S_1}{1+(S_1+\Delta S_1)H} + \frac{\Delta S_1}{1+(S_1+\Delta S_1)H}\right) i_1$$

Since $\Delta S_1$, in comparison to $S_1$ is very low *i.e.* effect of interfering input is low in comparison to desired input, then

$$O'_1 = \frac{S_1}{1+S_1H} i_1 + \frac{\Delta S_1}{1+S_1H} i_1$$

∴ Output due to change in transfer function on account of interfering input is

$$\Delta O_1 = \frac{\Delta S_1}{1+S_1H} i_1 \qquad \ldots(2)$$

Comparing equations (1) and (2), it will be seen that in latter case the change in output is reduced by a factor of $(1 + S_1H)$. If $H$ has high value, then the output on account of interfering input will be reduced considerably.

($c$) **Calculated output corrections.** This method can be used where the knowledge of effect of interfering input on output is known. Thus the error due to interfering input can be calculated and applying this correction to measured output, the output corresponding to desired input can be computed. This method can be used where temperature is the interefering input and its actual effect on output is known. Thus measuring the change in temperature, one can compute the real output.

($d$) **Signal Filtering.** This method employs filters so that the passage of interfering or unwanted signals is blocked in such a way that output on account of interfering signals is either completely eliminated or considerably reduced. Depending on application, the filter may be introduced either at input stage, or output stage, or intermediate stage.

In input filtering method, the interfering input is passed through a filter whose transfer function is ideally zero. However in most of the practical situations, interfering input is not available separately, but gets superimposed on desired input. In such situations the filters are designed so as to be selective, *i.e.* they should pass the desired input and reject or considerably attenuate the spurious signals. The filters could be in the form of mechanical devices or electrical/electronic circuits depending on application and requirements. Some examples of mechanical type filters are found in ($a$) isolation of vibrations and jerks to electro-

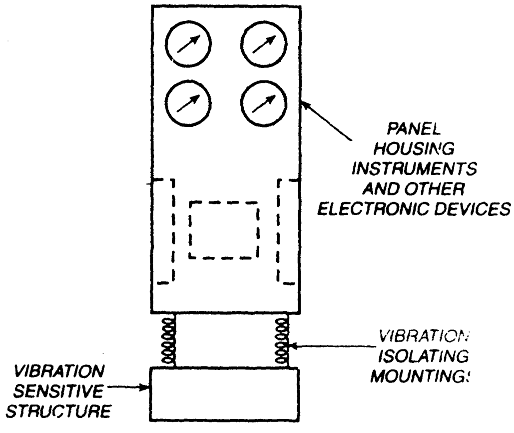


Fig. 1.3.

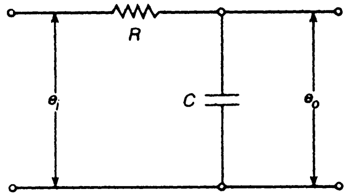
mechanical devices and delicate instruments used in aeroplanes, missiles etc. The interfering vibration inputs from the vibrating structure are filtered by a mass-spring system which transmits only a fraction of the vibrations to the panel housing instruments and other electromechanical devices (Refer Fig. 1.3).

Another example of mechanical type input filter is use of thermal insulation for reference junction of a thermocouple so that reference junction remains isolated from variations in temperature of environment, and output of thermocouple varies in direct proportion to change in temperature of measuring junction of thermocouple.

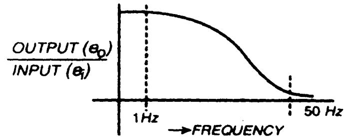
Other examples of mechanical filters are magnetic shield in the form of a box made up of a ferromagnetic material which houses the circuit to be isolated from influence of 50 Hz magnetic field created by power frequency fields in adjoining areas.

The pulsations in the air pressure of a large storage tank caused by air being fed by a reciprocating compressor can be smoothened (filtered) out by a pneumatic filter which consists of a flow restriction (a nozzle or orifice) housed in a capillary connected between the air reservoir and a small vessel connected to a pressure measuring device.

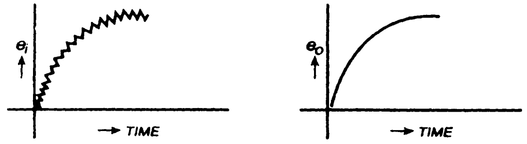
**Electrical Filters** are commonly used. These take the form of RC low pass filters and highpass filter. Low pass filters are used to eliminate high frequency noise signals super-imposed on useful signal. Highpass filter eliminates low frequency spurious signal superimposed on high frequency useful signal. The characteristics of these filters are shown in Figs. 1.4 and 1.5.



(*a*) Low pass Filter.



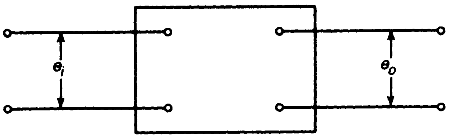
(*b*) Characteristics of Low pass Filter.



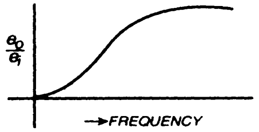
Input to Filter Output of Filter

(*c*)

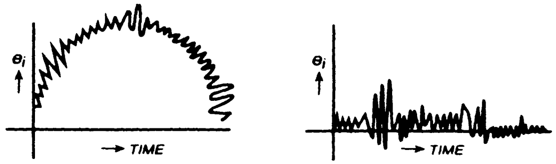
Fig. 1.4. Low Pass Filter.



(*a*) High pass Filter.



(*b*) Characteristics of High pass Filter.



Input to Filter Output of Filter

(*c*)

Fig. 1.5. High Pass Filter.

Referring to Fig. 1.4, it would be seen that characteristics of low pass filter is such that it passes low frequency signals as such or in amplified form, but high frequency signals are attenuated. Reverse is the case in case of high pass filter. Thus when noise in the form of high frequency super-imposed on useful signal is fed to low pass filter, its output after attenuating high frequency signal provides output of slowing varying useful signal.

In the case of high pass filter, the useful signal is in the form of high frequency signal but spurious signal of slowly varying type is superimposed on high frequency useful signal. After passing through high pass filter, the slowly varying (low frequency) spurious signal is eliminated and the high frequency signal without modulation is the output.

The example of use of low pass filter is experienced in avoiding noise pick up by strain gauge circuit. Fig. 1.6 shows an arrangement which is used for measurement of strains that are mainly steady and do not vary more rapidly than say 1 Hz. Ideally, the output signal should vary at the same rate as the input. However, the output from the strain gauge bridge may pick up signals from 50 Hz power lines, thereby distorting the output. Therefore, it is essential that the 50 Hz signal be eliminated so that there is no spurious signal applied to the measurement circuit.

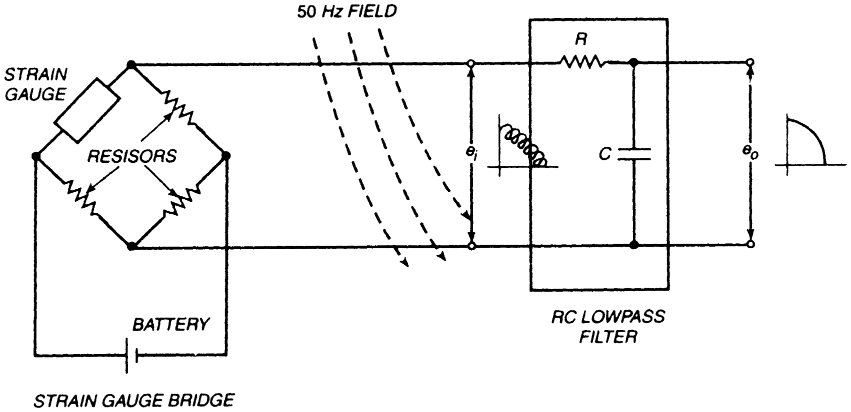


Fig. 1.6. Strain gauge circuit.

High pass filter is used in applications where the spurious input is a slow varying signal. A chopped radiometer as shown in Fig. 1.20 in a simplified form is used to sense the temperature, $\theta_s$, of an object in terms of the infrared radiant energy it emits. The emitted energy is focussed on a detector, a photo-emissive cell, which responds to this type of radiation. The radiant energy changes the temperature, $\theta_d$, of the photocell. Since the detector is sensitive to changes in temperature, it will produce a voltage $e_i$ which is amplified to $e_o$ by an amplifier. Thus if $\theta_s$ changes the temperature of the detector $\theta_d$ changes, with the result that $e_i$ changes and consequently the output voltage $e_0$ changes.

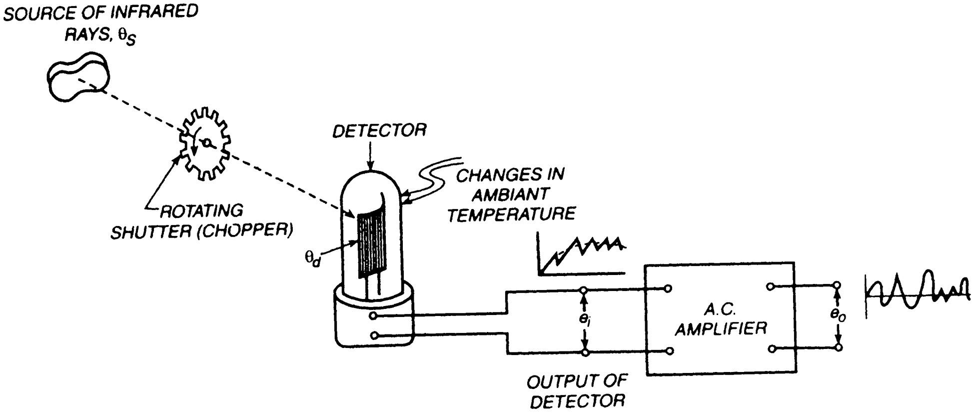


Fig 1.7.

The major problem with these devices is that the ambient temperature $\theta_{ambient}$ as well as the temperature of the source $\theta_s$ affect the temperature of the detector, thus affecting the output voltage $e_0$. The effect is serious because the radiant energy to be measured causes very small changes in $\theta_d$. On the other hand even small changes in ambient temperature, $\theta_{ambient}$, may completely distort the output, thereby completely shrouding the output signal. A simple solution to this problem is the introduction of a rotating shutter between the radiant source and the detector so that the desired input is chopped or modulated, at a known frequency. The modulating frequency is chosen to be much higher than the frequencies at which the change in ambient temperature occurs. The output voltage signal $e_i$ of the detector is a superimposed signal with slow changes on account of ambient temperature variations and a high frequency signal whose amplitude varies in accordance with $\theta_s$. In Fig. 1.7, the dotted line in input wave to amplifier shows effect of slowly varying ambient temperature and the solid line shows the effect of source temperature. As the desired and the interfering inputs are widely separated in frequency band, they can be conveniently and selectively filtered. For such an application, it is desired that the filter used should reject the slow varying interfering outputs on account of temperature variations, but pass fast varying signals on account of variations in $\theta_s$. This requires the use of a *a high pass filter.* In this case a.c. amplifier acts both as amplifier and high pass filter.

(*e*) **Method of opposing Inputs.** In method of opposing inputs the measurement system is so designed that the outputs caused by spurious inputs are opposed by outputs produced by components physically built into the system that exactly act the opposite way and cancel out the outputs on account of spurious signals.

Let us consider the case of measurement of strain in a cantilever beam with the help of strain gauge bridge as shown in Fig. 1.8. Temperature is an interfering input and there is an output on account of changes in ambient temperature even though there is no input strain. This effect can be eliminated by using a *dummy gauge* in the adjacent arm of the Wheatstone bridge. The arrangement is shown in Fig. 1.8.

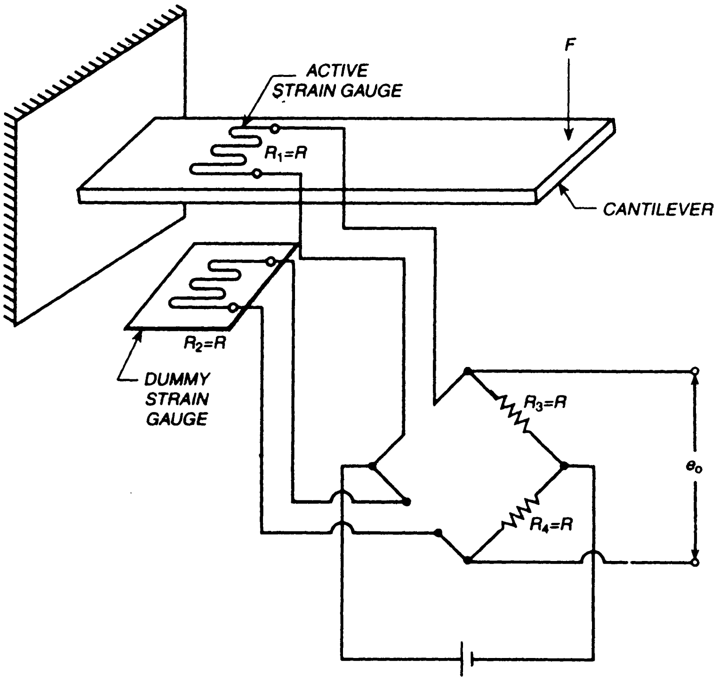


Fig. 1.8. Use of dummy gauge for ambient temperature compensation.

The active strain gauge is installed on the cantilever while the dummy gauge is installed on a like piece of material placed in the vicinity but is not subjected to any strain.

The bridge is initially balanced and therefore $R_1/R_3 = R_2/R_4$. Supposing a change in temperature occurs, and the resistances of active and dummy gauges change by $\Delta R_1$ and $\Delta R_2$ respectively. In order that there should be no output the bridge should be balanced and this requires

$$\frac{R_1+\Delta R_1}{R_3}=\frac{R_2+\Delta R_2}{R_4} \quad \text{or} \quad \frac{\Delta R_1}{R_3}=\frac{\Delta R_2}{R_4}$$

Let $R_3 = R_4$. Now bridge will be balanced if $\Delta R_1$ is equal to $\Delta R_2$. Now if the active and the dummy gauges are identical *i.e.* $R_1 = R_2$ and if the dummy gauge is placed in the same environments as the active strain gauge then $\Delta R_1 = \Delta R_2$ and, therefore, there will be no output due to changes in ambient temperature.

## 1.10. Functions of the Instrument

It has already been pointed out that the primary sensing element of the instrument first utilises energy from the measured medium to produce a condition representing the value of the measured variable. Then a secondary element known as transducer which merely converts the condition produced by the primary element into a more useful quantity, usually an electrical impulse which can be amplified sufficiently to operate the actuating mechanisms. Sometimes a manipulation element is also incorporated in between which modifies the signal of the transducer, *e.g.*, it may correct the non-linearity in the preceding coversion processes or may automatically compensate for change of temperature etc.

Finally the output is indicated in the form of a movement of the needle. This final instrument may be required to do the following functions :

(*i*) *Indication.* The value of the quantity can be read by the movement of needle on a calibrated scale provided in the instrument. Readings can be taken to any fraction within the limitations of the instrument and the human eye. Nowadays digital display (*i.e.* the reading in numericals) is also commonly used.

In fact where highly accurate and exact readings are desired, use of digital readouts is recommended.

(*ii*) *Signalling.* In this case the instrument is provided with signalling contacts which can be set at any value throughout the scale of the instrument. When the indicating needle shows the reading corresponding to the value at which signalling contact has been set, a contact is made or broken which can be utilised for initiating audible or visual alarm or for taking some corrective action in the plant automatically. The various combinations of signalling contacts can be achieved in order to meet different requirements. In certain instruments, no indication is required and only switches are provided, which make a limit switch contact through when that condition has reached. Signal monitor cards which actuate a contact at desired set value can be used with 4-20 mA current signal output of transducers, the same current signal also being used for other purposes like indication or control.

(*iii*) *Registering.* In such instruments the instrument merely indicates, by numbers or some other symbol of discrete increments, the value of some quantity.

(*iv*) *Recording.* In this case the instrument continuously records, with pen and ink, the value of the measured quantity against some other variable or against time. A graph paper is provided whose speed can be adjusted. A recording instrument can be used to record more than one number of quantities also, in which case, either the recording of different parameters may be done by different pens or same pen may record one parameter after other.

(*v*) *Transmitting.* In certain instances, transmitters are also provided in the instrument which provide a signal corresponding to the value of the quantity being measured. This signal can be used either for indication at some other place or for automatic control.

(*vi*) *To perform various manipulations.* In certain cases, instruments may be required to do operations such as addition, subtraction, multiplication, differentiation, integration, ratio control etc. Sometimes instruments are used to find solution of rather larger [illegible] algebraic or differential equations.

## 1.11. Static Measurements

Static measurements deal with the measurement of those quantities which remain constant. These measurements are as important as dynamic measurements. Separate type of instruments are required for each application as each has got different requirements to be fulfilled by measuring instruments. We shall now study some of the main factors associated with the static measurements such as indicating instruments of the scale and pointer type, calibration procedure, errors in measuring instruments.

## 1.12. Scale and Pointer Type of Indicating Instruments

These employ some form of element for transforming the quantity being measured into a deflecting force acting on the pointer movement. The pointer moves over a scale either in straight line or in a curve and the scale is calibrated in terms of the quantity being measured. Wherever possible, the scales are made uniform. The pointer generally remains in the 'zero' position when the instrument is not in use. For this purpose a restoring force is provided to constrain the pointer movement by some spring or by other means. When the instrument is used to make measurements, the deflecting force acts in opposition to this restoring force, till a balance is striked and pointer comes to rest where the reading is noted down.

## 1.13. Definitions

We shall now define some important terms used in connection with measuring instruments.

(*i*) *Range.* It represents the highest possible value that can be measured by an instrument. It has a very important bearing on the expected accuracy of the instrument. Usually the range of the instrument is selected such that for the working parameter the pointer deflection is about 2/3rds of the full scale, *e.g.,* if a pressure of about 11 kg/cm$^2$ is to be gauged them pressure indicator of range $11 \times 3/2 = 16.5$ kg/cm$^2$ (standard range available being 0–16 kg/cm$^2$) may be selected. The human error in observing the position of the pointer in respect to a scale marking is independent of the actual deflection, but this error has less effect on the overall accuracy with increasing deflections. If the lowermost reading is not zero but say $x$ units and highest point is $y$, then range of instrument is said to be from $x$ to $y$ and span of the instrument is $y–x$.

(*ii*) *Scale sensitivity.* It is defined as the ratio of a change in scale reading to the corresponding change in pointer deflection. It actually denotes the smallest change in the measured variable to which an instrument responds. Obviously if scale sensitivity is large, the overall accuracy of the instrument is small because a small change in pointer position, which can't be read as accurately as a large change, is equivalent to a large indicated change in the value of the measured quantity.

(*iii*) *Scale Readability.* In analog instruments, scale readability indicates the closeness with which the scale can be read. Scale readability depends on number of graduations, spacing of graduations, size of pointer, parallax effects, discriminating power of observer, etc.

(*iv*) *Repeatability.* It is a measure of closeness with which a given input can be measured over and over again. It is defined as the variation of scale reading and is random in nature.

(*v*) *True or actual value.* It is the actual magnitude of a signal input to a measuring system which can only be approached and never evaluated.

As the measurement process inevitably alters the characteristics of both the source of the measured quantity and the measuring system itself, there will always be some difference between the indicated value and the actual value.

(*vi*) *Indicated value.* The magnitude of a variable indicated by a measuring instrument is known as indicated value.

(*vii*) *Correction.* It is the revision applied to the indicated value so that the final result obtained improves the worth of the result.

(*viii*) *Overall error.* It is the difference of the scale reading and the true value. It is positive if the indicated value of the input quantity is in excess of its true value. Generally the error varies in sign over the whole range of the instrument with a mean value very nearly zero. The consistent bias in error is very rare if the instrument is properly designed and correctly adjusted.

(*vii*) *Sensitivity.* It is defined as the ratio of output response to a specified change in the input.

(*a*) *Resolution sensitivity.* It is the minimum change in the measured variable which produces an effective response of the instrument. It may be expressed in units of the measured variable or as a fraction or per cent of the full scale value or of the actual value. Resolution is also called discrimination.

(*b*) *Threshold sensitivity.* It is the lowest level of the measured variable which produces effective response of the instrument.

(*x*) *Hysteresis.* It is the difference between the increasing input value and the decreasing input value which effect the same output value.

(*xi*) *Accuracy.* It is the degree of correctness with which a measuring means yields the 'true' value with reference to accepted engineering standards, such as the standard meter, gram etc. It is assured that a true value always exists even though it may be impossible to determine. Accuracy is determined as the maximum amount by which the result differs from the true value. It may be expressed as a percentage based either on actual scale reading or full scale-reading. Accuracy of an instrument is influenced by factors like static error, dynamic error, reproducibility, dead zone.

It may be noted that the percent accuracies on basis of actual scale or full scale-reading are normally used to express equipment accuracies and do not include procedural or personnel performance which is actually included by the total error.

(*xii*) *Uncertainty.* It denotes the range of error, *i.e.* the region in which one guesses the error to be.

(*xiii*) *Error Calibration Curve.* It is an error curve which can be used for correcting instrument readings. The curve is plotted by calibrating the instrument against a suitable standard at a number of points on the scale.

(*xiv*) *Dead zone.* It represents the value within which the measured value can change without instrument responding to it, or it is the range within which variable can vary without being detected.

(*xv*) *Dead Time.* Time before the instrument begins to respond after the measured quantity has been changed.

(*xvi*) *Speed of response.* It is the quickness of an instrument to read the measured variable.

(*xvii*) *Precision.* It is the degree of reproducibility among several independent measurements of the same true value under specified conditions. It is usually expressed in terms of the deviation in measurement.

(*xviii*) *Significant Figures.* It is an indication of the precision of measurement. Significant figures convey actual information regarding the magnitude of precision.

(*xix*) *Linearity or non-linearity.* Deviation of transducer output curve from a specified straight line. Two common types of non-linearity are :

Terminal Linearity : Deviation from a straight line through the end points.

Best-fit Linearity : Deviation from the straight line which gives minimum errors, both plus and minus.

(*xx*) *Hysteresis.* The maximum differences in output at any measured value within the specified range when approaching the point first with increasing and then with decreasing input.

(*xxi*) *Repeatability.* The ability of a transducer to repeat readings consecutively under duplicate conditions of input and direction.

(*xxii*) *Drift.* An instrument is said to have no drift if it reproduces same readings at different times for same variation in measured variable.

*Zero drift*—Drift is called zero drift if the whole of instrument calibration gradually shifts over by the same amount. It may be due to permanent set or slippage and can be corrected by shifting pointer position.

*Span drift.* If the calibration from zero upwards changes proportionally, it is called span drift and may be due to change in spring gradient etc.

(*xxiii*) *Error Band*—The band of maximum deviations of output values from a specified line or curve.

*Note.* Specify conditions, *e.g.* temperature range, over which error band applies.

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

(*xxv*) *Zero balance (offset).* The electrical output of the transducer with no input applied.

(*xxvi*) *Temperature range*

(*a*) *Operating and Storage* : The range of temperatures over which the transducer will not suffer any damage or permanent change in characteristics.

(*b*) *Compensated* : The range of temperatures over which performance will remain within specified limits.

(*xxvii*) *Thermal zero shift (zero TC).* The change of zero (unbalance) due to changes in ambient temperature with no input applied. Usually expressed as % FS/°C.

(*TC*–temperature compensation, *FS*–full scale)

(*xxviii*) *Thermal sensitivity shift (span TC).* The change of sensitivity due to change in ambient temperature. Usually expressed as percentage of reading per °C.

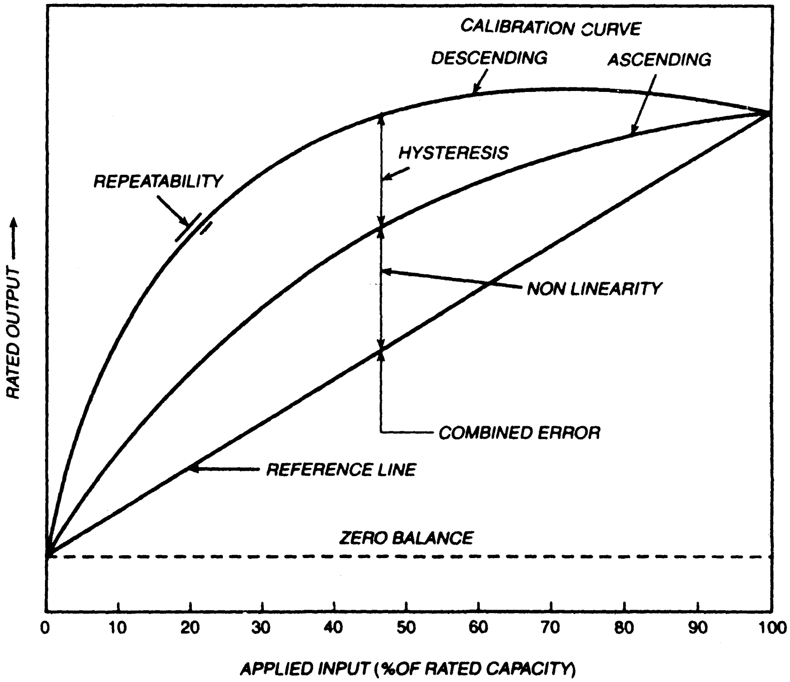


Fig. 1.9.

(*xxix*) *Deviation in measurement.* It is a statistical number representing the randomness among independent measurements of the same true value.

Deviation is variously expressed as :

(*a*) the difference between any measurement and the mean value of two or more observations;

(*b*) the average of several independent variations from the mean (the average deviation);

(*c*) the root mean square value computed from several individual deviations (standard deviation);

(*d*) the ratio of (*a*) or (*b*) or (*c*) to the mean. In any case the number of observations should be stated.

(*xxx*) *Noise.* Extraneous disturbances generated in a measuring system which conveys no meaningful information w.r.t. desired signal.

(*xxxi*) *Multi-sample test.* In multi-sample test, repeated measurements are made of a given condition by using altered test conditions, *i.e.* different observers and different measuring instruments. It may be noted that taking repeated readings with the same procedure and equipment does not give multi-sample test results.

If it is desired to know the exactness of a measurement, then the results of multi-sample tests must be analysed by the application of statistics.

(*xxxii*) *Single-sample test.* In single-sample test a single reading or a succession of readings are taken under identical conditions except for time.

(*xxxiii*) *Sensitivity and damping.* Most of the mechanical and electrical type indicating instruments depend on equilibrium for correct indication *i.e.* when the equilibrium is disturbed by a change of input, the system requires time to readjust to the new equilibrium position, and a number of oscillations may take place before the new output is correctly indicated. The rate at which the amplitude of such oscillations decreases is a function of system's damping. If damping is very low then oscillations will continue for a long period of time. If considerable damping is provided, then there will be no oscillations and excessive time would be required for pointer to reach final indicating value. Theoretically, viscous damping does not change the inherent sensitivity. It is now obvious that optimum damping should be provided so that equilibrium is reached as quickly as possible and at the same time maximum sensitivity is attained which is one of the factors determining accuracy. It may be noted that sensitivities greater than required should be avoided because sensitivity is gained at the expense of frequency response. Actually the frequency of oscillation is a function of both damping and sensitivity. A more sensitive instrument oscillates more slowly than the less sensitive instrument.

(*xxxiv*) *Reproducibility.* This is a very important requirement in the instruments particularly where exact quality of control is desired. It is defined as the degree of closeness with which the same value of a variable may be measured at different times. Reproducibility is affected due to several factors such as drift in the calibration of a thermocouple at high temperature due to contamination. Periodic checking and maintenance of an instrument are generally done to obtain reproducibility.

(*xxxv*) *Dead Zone.* It is the largest range through which the measurable variable can change without the change being indicated by the indicator. In case instruments are used for automatic controls then the initial impulse to the controller is fed with some time delay. The dead zone is also dependent upon the rate of change of variable and it becomes very serious (of high order) if the variable changes at a slower rate.

## 1.14. Time Element in Measurement

In the measurements and automatic controls; complete and immediate response to a change in a variable is an ideal condition and it is impossible to achieve it. Generally the response starts immediately but it takes a long time to complete its effect. Actually the lag or time element which makes the system sluggish and delays the response are contributed due to the responses of the measuring means, the controlling means and the process. Lag is the falling behind, or retardation, of one physical condition with respect to another physical condition to which it is related. Why lag comes in the measurements is obvious from the illustration of temperature measurement. In industrial practice the thermometer primary element is almost invariably mounted in a thermal well to protect it from the process fluid and to make possible withdrawing, checking and replacing the element without interrupting process operation. The thermal well, the mass of the sensing element, both introduce a considerable time lag in the response of the measurement. If it is analysed further then it will be found that the lag in measuring means occurs in (*i*) the primary element, (*ii*) the transmission system, and (*iii*) the measuring element of the instrument. When the measurement is used for control, this lag can have rather startling effects. Further as the lag is dependent upon the responses of the measuring means, the controlling means and the process; the rate of change of a variable is quite as important as the magnitude of change.

### 1.14.1. Effect of Instrument Lag on Dynamic Response

Let us consider bath of liquid in which some temperature element is inserted to determine the temperature. Let us increase the bath temperature at constant rate. Initially the thermometer is showing the same temperature as of the bath, but after a short time, the measured temperature lags the bath temperature by a constant amount. (Fig. 1.10). The difference between the true and the measured temperature is called the dynamic error. Lag coefficient is defined as the ratio of dynamic error and the rate of change of the measured variable.

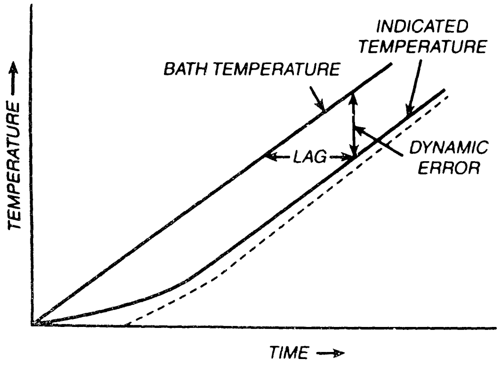


Fig. 1.10.

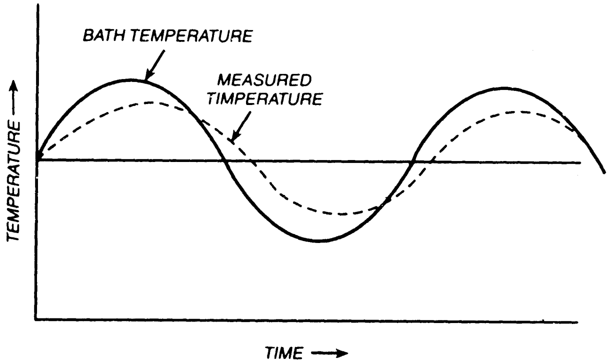


Fig. 1.11.

It may be noted that whenever the measurable variable is changing, there will always be dynamic error of measurement and its value can be made smaller by decreasing the measuring lag as much as possible. In automatic controls, where the operating conditions are seldom static, the dynamic error is usually more important than the static error. How the measured temperature of a bath will show when its temperature is varying in a sinusoidal manner is depicted in Fig. 1.11.

It is obvious from Fig. 1.11 that the lag of the primary element causes the cycle to be delayed and the amplitude is reduced.

It is reduced in amplitude because the bath temperature reaches one extreme of its cycle swing and starts in the other direction before the measured value catches up with it. The measured value meets the bath temperature going back in that direction and changes in direction before it reaches the cycle's extreme, and so it, too cycles, but not so extensively. From this curve it is obvious that the dynamic error prevents the indicator from showing true conditions at the process. Further the dynamic errors make the measurement appear smooth and stable though there may be overshoot and instability which may adversely affect product quality or processing operation. If lags exist in the measurement, either inherently or resulting from an application practice (such as thermometer wells), it is almost always possible to make allowances for taking care of this without serious effect on process operation. For optimum results, the dynamic as well as static characteristics of measurement must be recognised and allowances made for. The static error of measurement is the deviation of the instrument reading from the true value of a static variable. Large static lags are undesirable but are not necessarily detrimental to automatic control particularly where the variable is to be held at a constant value than at an exact value. (For Fig. 1.11, refer solved problems at the end of this chapter.)

## 1.15. Calibration Procedure

All instruments must be checked for accuracy at regular intervals as specified by the manufacturer. However, for special purposes, the special calibration has also to be carried out and the technique adopted depends on the ultimate accuracy desired. The calibration of the instruments is carried out in laboratories by a sub-standard which is used only on rare occasions specially for this sole purpose. These sub-standards are periodically checked against some standard held permanently in a metrological laboratory and this in turn is checked by some form of absolute measurement of the quantity which the instruments are designed to measure.

In the laboratory the readings of the instrument are compared with those of the sub-standards at several points along the scale and a calibration curve is then plotted.

The above argument holds good mainly for mechanical measurements. In process measuring instruments, calibration is carried out by feeding the known magnitudes of the basic input quantity to the detector-transducer and observing the system's behaviour. If the system has been proved linear, perhaps single point calibration will suffice, otherwise a number of values must be used and their results observed. Generally static inputs are applied and the dynamic response of the instrument is based on the static calibration. In certain cases it is impossible to introduce an input quantity for calibration purposes such as bonded strain gauges and then one has to rely on the spot calibration which is carried out by manufacturer and he does it by taking a sample out of a lot produced under statistical controls.

## 1.16. Loading Effects and Loading Errors

Ideally an element used for signal sensing, conditioning, transmission or detection should not alter the original signal. The sensing element should not use any energy or take least energy from the process so as not to alter the parameter being measured. This means that the original signal should not be distorted in any form by the introduction of any element in the measurement system. However, under practical conditions the introduction of any element in a system results, invariably in extraction of energy from the system thereby distorting the original signal. This distortion may take the form of attenuation, waveform distortion, phase shift etc. This makes measurements erroneous. The incapability of the system to faithfully measure the input signal in undistorted form is called the loading effect and this results into loading errors.

The loading effects not only occur in detector and transducer stage but may also occur in signal conditioning and presentation stages. The detector-transducer loads the input signal, the second stage loads the first stage, and finally the third stage loads the second stage. In fact, the loading problem is carried right down to the basic elements themselves.

In measurement systems we deal with both electrical and mechanical quantities and thus loading effects may occur on account of both electrical and mechanical elements. The loading effects are due to impedances of the various elements connected in a system. It is, therefore, desirable to analyze the effects of impedances.

It is possible to treat mechanical impedance similar to electrical impedance and thus we confine our study to electrical impedances.

### 1.16.1. Input Impedance

Fig. 1.12 shows a voltage signal source and an element called input device connected across it. The magnitude of the impedance of element connected across the signal source is called the *input impedance.*

The magnitude of the input impedance is given by :

$$Z_i = \frac{e_i}{i_i}$$

The instantaneous power extracted by the input device from the signal source is :

$$p = e_i \, i_i = \frac{e_i^2}{Z_i}$$

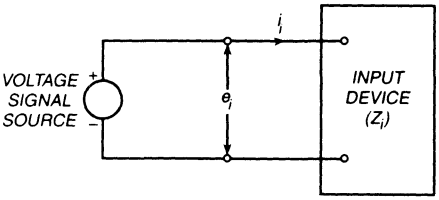


Fig. 1.12. Voltage signal source and input device having impedance $Z_i$.

From above Equations, it is clear, that a low impedance device connected across the voltage signal source draws more current and drains more power from signal source than a high impedance device.

Thus when an instrument is connected across the system for measurements, the system conditions change from the original conditions on account of the power drawn from the system. The amount of deviation from the original conditions depends upon the input impedance of the device. The lower the input impedance, higher is the power extracted and higher is the distortion of the original signal. A low impedance voltmeter loads the system heavily and thus results in wrong measurements. Ideally a voltmeter should not draw any power from the system and this is possible only if the voltmeter has an infinite value of input impedance.

### 1.16.2. Input Admittance

While many transducers produce voltage signal proportional to parameter being measured, some transducers produce current signal. In such cases series input devices are used. The concept of *input admittance* is used in such cases.

Fig. 1.13 shows a constant current source and an input device connected across it.

The magnitude of input admittance is given by :

$$Y_i = \frac{i_i}{e_i}$$

Input $Z_i = \frac{e_i}{i_i} = \frac{1}{Y_i}$

The instantaneous power extracted from signal source is :

$$p = i_i \, e_i = \frac{i_i^2}{Y_i}$$

$$= i_i^2 \, Z_i$$

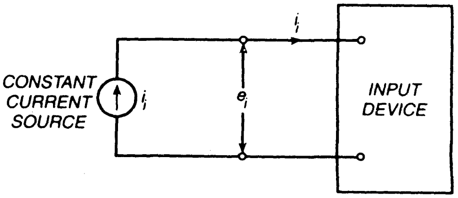
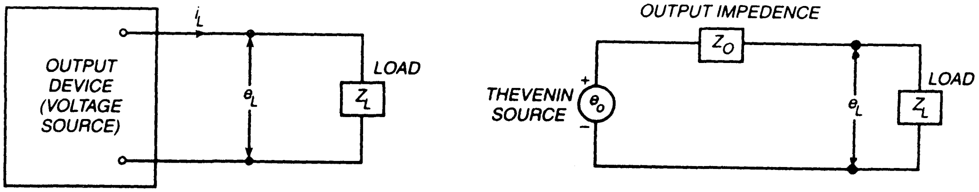


Fig. 1.13. Current signal source and input device having admittance $Y_i$.

From above equations, it is clear, that in case of series elements the power drawn from the current signal source is small when the input admittance of the device is high *i.e.,* input impedance is low. Therefore in case of series devices, the loading effects are small when their input admittance is large (*i.e,* when their input impedance is small). An ammeter, which is a series device, thus should be designed with a low input impedance so that the current is correctly measured.

### 1.16.3. Output Impedance

When a transducer is connected across a measuring instrument, the transducer can be seen as output device also. The output impedance of a device is defined as its equivalent impedance as seen by the load. The term *equivalent impedance* implies that the device can be represented by a *Thevenin's equivalent circuit* as shown in Fig. 1.14 (*b*).



(*a*) (*b*)

Fig. 1.14. An active bilateral device and its Thevenin's equivalent circuit.

Let $e_0$ = voltage appearing across the output terminals of the device when the load is not connected, and

$e_L$ = voltage appearing across the output terminals when the load is connected.

The *output impedance* of an active device is defined as :

$$Z_o = \frac{e_0 - e_L}{i_L}$$

It is clear from this equation that the drop in the output voltage $e_o - e_L = i_L Z_o$, is determined directly by the output impedance as the system is loaded. It is also clear that lower the output impedance, the lesser is the effect of load on the output voltage.

Power loss in voltage source $p = (e_o - e_L)\, i_L = i_L^2 Z_0$

Thus, for voltage sources, the lower the output impedance the lower is the voltage drop and also lower is the power consumption. Ideally there should not be any loading effect and this requires that output impedance $Z_0$ of the voltage source be zero or as low as possible.

### 1.16.4. Output Admittance

Output admittance is considered when dealing with current sources. The output admittance of current source is defined as :

$$Y_o = \frac{i_0 - i_L}{e_L}$$

where $i_0$ = current delivered by the constant current source,

$i_L$ = current flowing through the load when it is connected to the source.

$$\therefore \quad Y_0 = \frac{1}{Z_0}$$

Power loss in the current source $p = (i_0 - i_L)\, e_L = e_L^2 Y_0 = \frac{e_L^2}{Z_0}$

It is obvious from above equation that power drained from the current source is small if its output admittance is small or when its output impedance is large. Ideally for no power loss in a current source its output admittance should be zero and output impedance infinite.

### 1.16.5. Loading Effects due to Shunt connected Instruments.

In measurement systems, displaying instruments are connected across the transducer in parallel.

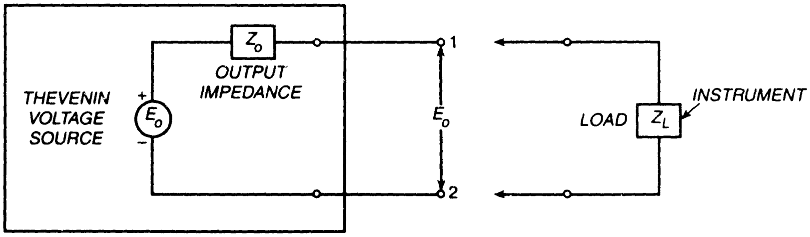


Fig. 1.15.

Consider a transducer comprising network consisting of linear bilateral impedances and generator with output terminals, 1 and 2 as shown in Fig. 1.15. This is a blackbox with a Thevenin generator of voltage $E_0$ and an output impedance $Z_0$ in series with the generator. Let $E_0$ be the open circuit voltage *i.e.* the voltage that appears across the terminals $A$ and $B$ when the load (measuring or recording device) is not connected to the terminals.

Ideally, when the load is connected across terminals 1 and 2, the output voltage should remain the same. However, the load impedance is not infinite and therefore when a voltmeter with an input impedance $Z_L$ is connected across $A$ and $B$, a current $I_L$ flows. This causes a voltage drop $I_L Z_0$.

∴ Output voltage under loaded condition changes to $E_L$ from $E_0$ and

$$\mathbf{E}_L = \mathbf{E}_0 - \mathbf{I}_L\mathbf{Z}_0 = \mathbf{I}_L\mathbf{Z}_L$$

or

$$\mathbf{E}_0 = \mathbf{I}_L\,(\mathbf{Z}_L + \mathbf{Z}_0)$$

∴ Ratio of actual voltage appearing across the load to the voltage under no load conditions is :

$$\frac{E_L}{E_0} = \frac{I_L Z_L}{I_L(Z_L + Z_0)} = \frac{1}{1 + Z_0/Z_L}$$

∴ Actual voltage measured is : $E_L = \dfrac{E_0}{1 + Z_0/Z_L}$

Obviously the voltage $E_L$ as measured is distorted (both in phase and magnitude) on account of connection of measuring instrument across it.

It is also clear from above equation that for the original signal $E_0$ to remain undistorted the value of input impedance of the instrument $Z_L$, should be infinite (or the value of output impedance of the source, $Z_0$ should be equal to zero).

Further in order to obtain as less distortion as possible the value of $Z_L$, the input impedance of instrument should be very high as compared with $Z_0$, the output impedance of the source.

**Example 1.1.** *A multimeter having a sensitivity of 150,000 Ω/V is used to measure the voltage across a thermocouple circuit having an output impedance of 10 kilo ohm. The open circuit voltage of the circuit is 0.05V. Find the reading of the voltmeter when it is set to its 0.1V scale. Find the percentage error and comment upon the results.*

**Solution.** Input impedance of voltmeter $Z_L = 150{,}000 \times 0.1 = 15k\Omega$

Output impedance of circuit $Z_0 = 10\ k\Omega$.

Open circuit voltage of circuit under measurement $E_0 = 0.05V$.

Reading of voltmeter is, $E_L = \dfrac{E_0}{1+Z_0/Z_L} = \dfrac{0.05}{1+\dfrac{10}{15}} = \dfrac{0.05}{1.67} \simeq 0.03V$

$\therefore$ Percentage error in voltage reading $= \dfrac{0.03-0.05}{0.05} \times 100 \simeq 40\%$

In this case error (loading) is very high because input impedance of multimeter is comparable with that of the impedance of the circuit under test.

For 99% accuracy in voltage measurement, the input resistance of the voltmeter should be 100 times greater than the output resistance.

### 1.16.6. Loading Effects due to Series connected Instruments

Let us now consider a network represented by a voltage source having a voltage $E_0$ and an output impedance $Z_0$.

The value of current flowing between terminals 1 and 2 under ideal conditions is $I_0$, when terminals 1 and 2 are shorted.

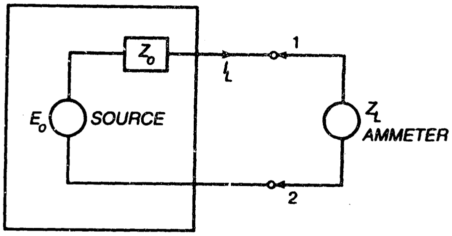


Fig. 1.16. Loading effect of series connected instruments.

$$I_0 = \frac{E_0}{Z_0} \quad \text{or} \quad E_0 = I_0 Z_0.$$

However for measuring the current, a current measuring device is introduced between terminals 1 and 2 which adds to the impedance of circuit and modifies the value of current.

Suppose $Z_L$ = input impedance of ammeter,

Measured value of current $I_L = \dfrac{E_0}{Z_0+Z_L} = \dfrac{I_0 Z_0}{Z_0+Z_L} = \dfrac{I_0}{1+Z_L/Z_0}$

In order that the measured value of current be equal to the actual value of the current, $I_0$, the value of $Z_0 >> Z_L$, or the input impedance of the ammeter should be very small as compared with the output impedance of the source.

In case of current sources, the relationships of currents under loaded and unloaded conditions in terms of admittances can be expressed as

$$I_L = \frac{I_0}{1+Z_L/Z_0} = \frac{I_0 Z_L}{Z_0+Z_L} = \frac{I_0/Y_0}{1/Y_0+1/Y_L} = \frac{I_0 Y_L}{Y_L+Y_0}$$
$$= \frac{I_0}{1+Y_0/Y_L}$$

From above equation it is clear that in order to avoid loading effects the input admittance of the ammeter should be very large as compared with the output admittance of the source.

### 1.16.7. Generalized Impedance & Stiffness Concepts

Let us consider measuring process for measurement of temperature of a bath by thermocouple. Bath has certain temperature. When thermocouple is inserted in bath it extracts some energy, lowering temperature of bath. The mV signal across thermocouple is to be measured by a multivoltmeter. When millivoltmeter is connected across it, the output signal is attenuated.

Thus the introduction of any measuring instrument in a measurement system results in extraction of energy from the system thereby resulting in *"Loading Effects"* causing a distortion of the measurand. In order to assess the imperfections in measurements it becomes imperative to introduce some means of analysis whereby it would become possible to determine the extent to which the measurand has been affected so that corrective measures can be taken up to eliminate these effects if possible or to minimize these effects. In order to understand the loading effects the concepts of *Static Impedance* and *Static Stiffness* need to be understood.

Loading effects occur due to extraction of energy from the measurand. The transfer of energy requires the specification of two variables. At the input of each element of a measurement system there exists a variable $v_1$ with which we are primarily concerned. At the same point, there is an associated variable, $v_2$. The dimensions of these two variables are such that their product has the dimensions of power *i.e.* $p = v_1 \times v_2$.

The above product represents the instantaneous energy of the system.

The physical variables which determine the flow of energy in all dynamical systems can be classified as :

(*i*) Through variables and (*ii*) Across variables.

**1. Through Variables.** (Also called flow variables and per variables). *Through variables* are those which can be specified and measured at one point in space. The through variables are extensive variables, in the sense, that their magnitude depends upon the extent of the system taking part in the energy transfer.

**2. Across Variables.** (Also called effort variables and trans variables). *Across variables* are those which can be specified and measured by two points in space. Usually one point is a reference point. The across variables are intensive variables whose magnitude is independent of the material being considered.

Time is a variable having a spatial independence. All objects in a measurement system or any dynamical system involve a measured or defined relationship between an *across variable* and a *through variable*. For instance, an electrical capacitor is defined in terms of the voltage (across variable) and the charge (through variable).

When we are primarily concerned with an input variable $v_1$, (across variable) and its associated variable $v_2$ (through variable), the generalized input impedance is :

$$Z_{gi} = \frac{v_1}{v_2}$$

The power drawn from the system is : $p = \frac{v_1^2}{Z_i}$

Here also a large input impedance is necessary to keep the power drain small.

The value of measured quantity is, $v_3 = \frac{1}{1 + Z_o / Z_i} v_4$

where $v_3$ = measured value of across variable,
$v_4$ = undisturbed value of across variable,
$Z_0$ = generalized output impedance of source,
$Z_i$ = generalized input impedance of measurement device.

Thus if $Z_o$ and $Z_i$ are known, then we can find value of measurand by means of equation (on previous page.) However, this is inconvenient. Also $Z_o$ is also not clearly known in non-electrical systems where definitions of both $Z_i$ and $Z_o$ are not always straight forward. Thus a high value of $Z_i$ is desirable since then corrections are unnecessary.

However, if $v_1$ is the through variable, the situation becomes quite different. In that case it is more convenient to use admittances instead of impedances.

The *Generalized Input Admittance* is defined as :

$$Y_i = \frac{\text{through variable}}{\text{across variable}} = \frac{v_1}{v_2}$$

The power extracted from the measurement system is,

$$p = v_1 v_2 = \frac{v_1^2}{Y_i}$$

$$(p = v_1^2 / Z_i)$$

Thus it is clear from above equations that a large value of input admittance $Y_i$ is required to limit the power extracted from the measurement system.

The value of measurand (which is through variable in this case), under loaded conditions, can be written as :

$$v_5 = \frac{1}{1 + Y_o / Y_i} \times v_6$$

where $Y_0$ = generalized output admittance of preceding element,

$Y_i$ = generalized input admittance of instrument,

$v_5$ = measured value of through variable,

and $v_6$ = undisturbed value of through variable.

Thus it is clear from Eqn. ($v_5 = v/(1 + Y_0/Y_1)$) that when a through variable is being measured, the value of the input admittance of the input element should be very large as compared with output admittance of the source.

### 1.16.8. Static Stiffness and Static Compliance.

In many instruments, the loading effect on the preceding stage is nil under static conditions. However, when the same instruments are subjected to dynamic conditions they produce loading effects because energy is required for these operations. Under these conditions, the concepts of impedance and admittance may not be useful and, therefore, it is appropriate to use the concepts of *Static Stiffness* and *Static Compliance*. It may be understood that while impedance and admittance are concerned with power drain, the stiffness and compliance are concerned with energy drain.

Let us consider force as across variable, then through variable = power/across variable

$$= \frac{\text{Nm/s}}{\text{N}} = \text{m/s} = \text{velocity}$$

Thus the through variable, associated with across variable force, is velocity.

∴ The mechanical impedance is given by : $\dfrac{\text{across variable}}{\text{through variable}} = \dfrac{\text{force}}{\text{velocity}}$

If we were to calculate the mechanical impedance of an elastic system by applying a constant force and noting the resultant velocity, then mechanical impedance will be :

$$\frac{\text{force}}{\text{velocity}} = \frac{\text{force}}{0} = \text{infinity (velocity of static system is zero)}$$

under such situations, the system is characterised using energy rather than power. Therefore a new term *Stiffness* has to be used. This term is associated with energy and not with power. Thus we define mechanical stiffness for this case as ratio of force and displacement:

In general the *Mechanical Stiffness* is defind as :

$$S = \frac{\text{across variable}}{\int (\text{through variable})\, dt}$$

The same formulae can be used for calculating the value of the output signals as were used for impedance except that stiffness is used in place of impedance.

Thus $$v_7 = \frac{1}{1 + S_o / S_i} \times v_8$$

where $v_7$ = measured value of across variable,

$v_8$ = undisturbed value of across variable,

$S_o$ = generalized static output stiffness of source,

and $S_i$ = generalized static stiffness of the input source.

When the measured variable is not the across variable, the admittance rather than impedance is a convenient. Similarly compliance is used instead of stiffness. *Compliance* is defined as inverse of stiffness.

$$\text{Compliance } C = \frac{1}{S} = \frac{\text{through variable}}{\int (\text{across variable})\, dt}$$

$$v_9 = \frac{1}{1 + C_o / C_i} \times v_{10}$$

where $v_9$ = measured value of through variable,

$v_{10}$ = undisturbed value of through variable,

$c_i$ = generalized static input compliance of measuring instrument,

and $c_o$ = generalized static compliance of measured system.

### 1.16.9. Impedance Matching and Maximum Power Transfer.

In practical applications it is desirable to *match* the impedance of the input device to the output impedance of the signal source. Many low frequency cases such as audio amplifiers, feeding loudspeakers and other electromechanical transducers require impedance matching for high power transfer.

Let us analyse the problem of maximum power transfer when the source and input device have only pure resistances. (See Fig. 1.17).

Let $E_0$ = voltage of the source under no load conditions,

$E_L$ = voltage of the source under loaded conditions.

$R_0$ = output resistance of the source,

and $R_L$ = input resistance of the load.

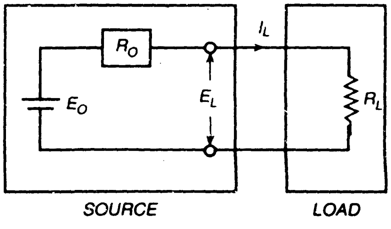


Fig. 1.17. Maximum Power Transfer.

The power delivered to the load is given by $P = \frac{E_L^2}{R_L}$

Since $E_L = E_0\, R_L/(R_0 + R_L)$, $P = \frac{E_0^2}{R_L}\left(\frac{R_L}{R_0 + R_L}\right)^2 = \frac{E_0^2\, R_L}{(R_0 + R_L)^2}$

Maximum power transfer takes place when $\frac{dP}{dR_L} = 0$.

Differentiating we have, $\frac{dP}{dR_L} = \frac{(R_0 + R_L)^2 E_0^2 - E_0^2 R_L \times 2(R_0 + R_L)}{(R_0 + R_L)^4} = 0$

which gives $R_0 = R_L$

Maximum power delivered to the load is

$$P_{max} = \frac{E_0^2}{(R_0 + R_L)^2} R_0 = \frac{E_0^2}{4R_0}$$

In case of a.c. circuits for maximum power transfer the impedance of the load should be made equal to the complex conjugate of the Thevenin equivalent impedance of the source.

Under conditions of maximum power transfer, the power supplied by source is,

$$\frac{E_0^2}{R_L + R_0} = \frac{E_0^2}{2R_0}$$

while the power delivered to the load is only $E_0^2 / 4R_0$.Therefore, under conditions of maximum power transfer the efficiency is only 50%.

**Example 1.2.** *Measurements on a thermocouple indicate an open circuit voltage of 32mV, and a current of 4 nA through a 5 MΩ load. What is maximum power available from the thermocouple ?*

**Solution.** Let $R_0$ be the internal resistance of the thermocouple, $I_L$ the load current and $R_L$ the load resistance.

$\therefore$ Open circuit voltage of thermocouple $E_0 = I_L\,(R_0 + R_L)$

or $32 \times 10^{-3} = 4 \times 10^{-9}\,(R_0 + 5 \times 10^6)$

Hence, output resistance of thermocouple $R_0 = 3 \times 10^6 \mathit{ohm}$.

Maximum power available from the thermocouple, $P_{max} = \frac{E_0^2}{4R_0}$

$$= \frac{(32 \times 10^{-3})^2}{4 \times 3 \times 10^6} = 85.3 \times 10^{-12}\ \text{W}.$$

## 1.17. Standards of Measurement

We shall first describe the primary standards of length, time, and mass and then see how some of the other standards are derived from these fundamentals. In strict sense, the term standard means a physical object which serves to preserve the value of some unit. It is, therefore, implied that the standard should be either permanent or definitely reproducible. As the words permanence and reproducibility are relative, each laboratory and plant is likely to have its own "standards" and thus the classification of standards is also very flexible. It is, therefore, considered better to classify standards into two categories, *viz.*, primary or basic standards, and secondary, derived, reference or working standards. The primary standards are those which constitute the ultimate basis of reference in accordance with which values are specified to secondary standards.

### 1.17.1. Primary standards : (Length, mass and time)

**Length.** For defining length the following standards are followed throughout the world :

(*i*) Bar Standards
(*ii*) End Standards
(*iii*) Light Waves Standards.

**Bar Standards.** The United States national standard of length is a metre bar, made of platinum-iridium alloy. The metre is defined by the distance between two lines ruled on the bar.

The British Unit Yard is defined as equal to 3600/3937metre.

**End Standards.** Nowadays trend is to use end standards which define a given unit, or multiple thereof, by the distance between the two ends. Standards of this type made of fused quartz, one decimetre long, have been used for international comparisons as well as for calibration of working standards of steel.

**Light Waves Standards.** The wavelengths of many special lines can be used as convenient and practical standards for calibrating gauges. For standards purposes, the red line emitted by cadmium vapour having a wavelength of 6438-4696 angstroms, in air of standard composition is considered as standard and according to it the metre bar is equal to 1,553,164.13 wavelengths of cadmium line.

Nowadays spectral lines of single isotope such as mercury 198 or krypton 84 is also considered for this purpose.

**Mass.** The United States national standard of mass, or of weight, is a cylinder made of platinum-iridium weighing 1 kilogram. Similarly the Britain maintains British Imperial pound as the standard of mass.

**Time.** The basic standard for measurement of time is the rotating earth, according to which it is found that the mean solar second is equal to the 86,400th part of a day. Secondary standards for this purpose, utilising electrical oscillating circuits, the frequency of which is controlled by piezo-electric quartz oscillators, have also been developed. Standard frequencies of various values, controlled by the oscillators, are broadcast continuously from radio station *WWV* with an accuracy of 1 part in 100 million. With appropriate radio receivers the broadcast time signals may be used to check local oscillators, clocks etc. The radio signals of any derived frequency are transmitted by "atomic clocks" which utilise crystal oscillators, the frequency of which is controlled by the resonance frequency of ammonia molecules in a wave guide.

### 1.17.2. Derived Standards and Units

Most of the units used to define the properties of materials and operation of processes are combinations of length, mass and time. For such cases, standards used are usually either measuring instruments of special quality previously calibrated by reference directly or indirectly to the basic standards or samples of substances having known properties predetermined by earlier measurements.

There are certain parameters for which no standard can be prescribed, *e.g.* kelvin scale of temperature for which International Temperature Scale has been established. This scale is defined by a combination of accepted numerical values for the freezing, boiling and melting points of certain substances. The accuracy of temperature-measuring instruments can also be checked by observing the melting points of certain standard samples of pure materials of which the melting points are accurately known.

### 1.17.3. Standard Samples

A variety of standard samples have been developed to provide checks on operation and on measuring instruments *e.g.*,

(*i*) Samples of irons and of steels of specified composition to check the correctness of chemical analysis of those materials.

(*ii*) Standard samples for roughness comparison of surfaces.

(*iii*) Standard samples of materials of specified density, viscosity, calorific value, colour, reflectance, gloss opacity or turbidity for checking the accuracy of instruments used to measure these properties.

(*iv*) Standard samples of alloys, ores, ceramic materials, chemical reagents and hydrocarbon etc.

### 1.17.4. Radiation Standards

Thermopiles or bolometers are used for measurement of thermal or heat radiation which is simply a transfer of energy. These instruments are calibrated by standard lamps which are exactly like those used as working standards of light, but certified to give a specified intensity of radiant power in a given direction when operated at a specified voltage or current.

The standard for the measurement of radiation produced by radioactive materials like radium is the tubes containing radium salts, with the amounts of the radium-element certified by an International Radium Commission. The amount of radium in a sample is found by comparing its intensity of gamma rays with that of the standard.

X-ray measurements in general are based upon the amount of ionisation which the rays produce in air.

### 1.17.5. Basic Electrical Standards

Originally the electrical units such as ohm, ampere, volt and watt were derived from the basic units of length, mass, and time in accordance with accepted electromagnetic theory. This task was really a very tough one and as such an "International" system of units based upon arbitrary standards was developed by a series of international electrical congresses, according to which international ohm was defined as the resistance of a specified column of mercury, and the international ampere as the current which would deposit silver in a voltmeter, or coulometer, at a specified rate.

**New "Absolute" Values.** As the nominal basic standards were not precise enough to meet modern needs, the real (practical reference) standards consisting of groups of wire resistors and of Weston standard cells came into use.

**Reference Standards for the Ohm.** At National Bureau of Standards, the reference standards of resistance are a group of ten 1 ohm coils made of manganin wire sealed in dry air in the space between the two walls of a double-walled metal container of cylindrical shape. The resistance of each standard is measured periodically, and the average of the ten is assumed to remain constant for the period between adjustments of values of the unit by international agreement.

**Reference Standards for the Volt.** Weston standard cells are primary batteries having electrodes of mercury and of cadmium amalgam, with a solution of cadmium sulphate as electrolyte. Two types of cells are made for different purposes, *viz.*, (*i*) saturated solution of electrolyte and (*ii*) unsaturated solution of electrolyte. In the first type the electrolyte is made a saturated solution by adding surplus crystals of cadmium sulphate. These have an electromotive force which remains very constant over long periods of time but is relatively sensitive to temperature, decreasing about 0.004% per degree centigrade rise. In the second type the electrolyte is made an unsaturated solution by properly choosing the value of concentration of cadmium sulphate. As differences in the concentration of cadmium sulphate affect the temperature coefficient of electromotive force, the change with temperature can be made negligible by choosing an appropriate concentration. About 25 cells are maintained at the National Bureau of Standards. These are tested from time to time and those showing little variation than average are discarded.

**Basic SI Units**

| *S. No.* | *Physical Quantity* | *Name of unit* | *Unit Symbol* | *Base of Definition* | *Definition* |
|---|---|---|---|---|---|
| 1 | Length | metre | m | Wavelength of red light in krypton 86 | 1,650, 673.73 wavelengths in vacuo of the radiation corresponding to the transition between the energy levels 2p 10 and 5d 5 of the krypton—86 atom. |
| 2 | Time | second | s | Cycles of radiation of cesium | The duration of 9, 192, 631, 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium—133 atom. |
| 3 | Mass | kilogram | kg | Platinum-cylinder prototype | Mass of the international prototype which is in the custody of the Bureau International des Poids et Mesures (BIPM) at Sevres, near Paris. |
| 4 | Temperature | kelvin | K | Absolute zero and water | The fraction 1/273.16 of thermodynamic temperature of the triple point of water. |
| 5 | Electric Current | ampere | A | Force between two conducting wires | The constant current which, if maintained in two parallel rectilinear conductors of infinite length, of negligible circular cross-section, and placed at a distance one metre apart in vacuum would produce between these conductors force equal to $2 \times 10^{-7}$ N/m length. |
| 6 | Luminous Intensity | candela | cd | Intensity of an area of platinum | The luminous intensity, in the perpendicular direction, of a surface of 1/600,000 square metre of a black body at the temperature of freezing platinum under a pressure of 101, 325 newtons per square metre. |
| 7 | Quantity of substance | mole | mol | Amount of atoms in carbon 12 | The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. |

### 1.17.6. Derived Electrical Standards

All these electrical standards and instruments can be calibrated by utilising the standard resistor and the standard cell. The choice of sequence and of procedure for calibrating standard capacitors, inductors, potentiometers, bridges, ammeters, voltmeters, watt-meters and watt hour-meters is a matter of convenience. However, for accurate work, both resistors and standard cells should be recalibrated periodically as the commercial types change their value with time.

## 1.18. International System of Units (SI).

It is the system established in 1960 by the (CGPM) General Conference of Weights and Measures and abbreviated as SI ("System International" unites) in all languages. The SI like the traditional metric system, is based on decimal arithmetic. For each physical quantity, units of different sizes are formed by multiplying or dividing a single base value by powers of 10. Obviously this offers great advantage because the changes can be made very simply by adding zeros or shifting decimal points. In the metric system we have been following so far, this simplicity of a series of units linked by powers of 10 is limited to plain quantities like length, and this simplicity is lost when more complex units like energy etc., are encountered. For example energy is now represented by several units like kg m, H.P., kW, etc. In contrast, the SI provides only one basic unit for each physical quantity, and universality is thus achieved.

The SI is coherent system, in the sense that the product or quotient of any two unit quantities in the system is the unit of the resultant quantity, *e.g.* if unit of length is metre, then unit of area will be square metre and not acres or *begas* etc.

The seven base SI units established by the General Conference of Weights and Measures are shown at page 30:

Other physical quantities are derived from these basic units. For example, volume is cubic metre ($m^3$), speed is metre per second (m/s). force is mass–metres per square second (m. kg/$sec^2$). Realising that some derived units may be complex array of base units, some units have been given special names. These are :

**SI units having special names**

| *Physical Quantity* | *Name of unit* | *Unit symbol* |
|---|---|---|
| Force | newton | $N = \frac{kgm}{s^2}$ |
| Work, energy, quantity of heat | joule | $J = N.m$ |
| Power | watt | $W = J/s$ |
| Electric charge | coulon | $C = A.s$ |
| Electric potential | volt | $V = W/A$ |
| Electric capacitance | farad | $F = C/V$ |
| Electric resistance | ohm | $\Omega = V/A$ |
| Electric conductance | siemen | $S = A/V$ |
| Magnetic flux | weber | $Wb = V.s$ |
| Inductance | henry | $H = \frac{V.s}{A}$ |
| Luminous flux | lumen | $lm = cd . sr$ |
| Magnetic flux density | tesla | $T = Wb/m^2$ |
| Illumination | lux | $lx = lm/m^2$ |
| Frequency | hertz | $Hz = (cycle)/s$ |
| Pressure | pascal | $Pa = N/m^2$ |

SI also recommends the use of supplementary units, the only authorised supplementary units being measured for plane and spherical angles. Though these could be expressed by base units but have been made available as a convenience to users. Plane angles are represented by radians, and solid angles by steradians.

Decimal multiples and submultiples of the SI units are formed by means of the prefixes given below, which represent the numerical factors shown :

| *Multiplication Factor* | *Prefix* | *SI Symbol* |
|---|---|---|
| $10^{12}$ | tera | *T* |
| $10^{9}$ | giga | *G* |
| $10^{6}$ | mega | *M* |
| $10^{3}$ | kilo | *k* |
| $10^{2}$ | hecto* | *h* |
| $10^{1}$ | 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* |

*To be avoided where possible.

The two major advantages of coherency of SI units are (*i*) same system and unit of measurement are used regardless of industry, trade, or discipline, and (*ii*) minimum of conversion factors are needed (other than powers of 10).

In connection with SI units, some rules of style, abbreviation, writing, and drafting practices are applied, some of which are described below :

(*a*) No dots, commas etc. are used after SI symbols except at the end of sentences. For example 32 metres will be written as 32 m and not as 32 m.

(*b*) Plurals are never used in connection with SI unit symbols, for example 32 metres will be written as 32 m and not as 32 ms which would mean 32 milli seconds.

(*c*) Decimal fractions are always started with O. For example, half metre will be written as 0.5 m and not as .5 m.

(*d*) Multiplication or times sign is " . " This is used between the numbers to be multiplied and between unit symbols in derived units where two unit symbols adjoin for the purpose of clarity, *e.g.* unit of torque may be written as m-N (metre-Newton) which if written as m N can be misunderstood as milli newton.

(*e*) All symbols and prefixes are lower case letters, except symbols derived from proper names, like W for watt, M, G, and T for the largest three power of 10 prefixes. All symbols should be used as they are to avoid any confusion.

(*f*) No degree mark (°) is used with kelvin, the unit of temperature. A temperature interval can also be expressed in degree celsius.

(*g*) Double prefixes should not be used, *e.g.* one kilo Megawatt may not be written as kMW, but as GW.

(*h*) The expression "per" in symbols of derived units is always indicated by a fraction line as m/s or $\frac{\text{m}}{\text{s}}$, but the word "per" or letter "*p*' should not be used for this purpose.

(*i*) Only the numerator should be multiplied by powers of 10 in compound derived units and the denominator should always remain the base unit.

For example 0.032 m/s may be put as 32 mm/s and not as 0.000032 m/ms.

(*j*) Numbers may be grouped in clusters of three in both directions from the decimal mark, and gap may be given for clarity and comma should not be used there, *e.g.* 153297.3 m may be written as 153 297.3 m and not as 153,297.3 m.

(*k*) Units with names of scientists should not be capitalised when written in full.

(*l*) According to SI recommendations, litre is a special name given to cubic decimetre and the word litre should not be used for expressing results of high precision volume measurements.

(*m*) Some units which though strictly incompatible with SI units, have been allowed initially, like km/hr, rev/min.

## UNSOLVED PROBLEMS

1. A recording instrument requires a current of 0.05 A to overcome initial fraction and produce motion of the movement. Define this effect and list factors which produce it. [**Ans.** Dead zone = 0.05 A]

2. The dead zone of a certain pyrometer is 0.125 per cent of the span. The calibration is 800°C to 1800°C. What temperature change must occur before it is detected ? [**Ans.** 12.5°C]

3. What is the true value of voltage across the 500 kΩ resistor connected between terminals A and B as shown in Fig. 1.18 ? What would a voltmeter with a sensitivity of 20 kΩ/V read on the following ranges : 50, 15, 5 volt ?
[**Ans.** 10 V, 9.75 V, 9.23 V, 8 V]

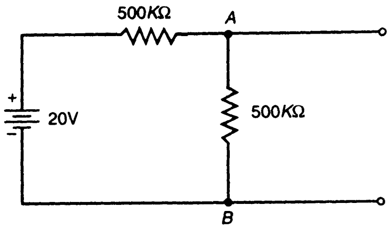


Fig. 1.18.

4. A high resistance voltmeter reads 8 V across a 4 Ω resistance connected to a battery; the voltage rises to 9 V when the resistance is increased to 9 Ω. Calculate the maximum power available from the battery. [**Ans.** 36.2 W]