

INTRODUCTION

1.1 MEASUREMENTS

Measurements are made or measurement systems are set up for one or more of the following functions:

1. To *monitor* processes and operations
2. To *control* processes and operations
3. To carry out some *analysis*

These functions are elaborated now.

1.1.1 Monitoring

Thermometers, barometers, anemometers, water, gas and electricity meters only indicate certain quantities. Their readings do not perform any control function in the normal sense. These measurements are made for monitoring purposes only.

1.1.2 Control

The thermostat in a refrigerator or geyser determines the temperature of the relevant environment and accordingly switches off or on the cooling or heating mechanism to keep the temperature constant, i.e. to control the temperature. A single system sometimes may require many controls. For example, an aircraft needs controls from altimeters, gyroscopes, angle-of-attack sensors, thermocouples, accelerometers, etc.

Controlling a variable is rather an involved process and is therefore a subject of study by itself.

1.1.3 Analysis

Measurements are also made to

1. test the validity of predictions from theories,
2. build empirical models, i.e. relationships between parameters and quantities associated with a problem, and
3. characterize materials, devices and components.

In general, these requirements may be called *analysis*.

1.2 INSTRUMENTS

Measurements are made with the help of instruments. Instruments, in general, consist of a few elements. But before we go into the contents of a generalized instrument, let us define what is meant by an instrument.

An instrument may be defined as a device or a system which is designed in such a way that it maintains a functional relationship between a prescribed property of a substance and a physical variable, and communicates this relationship to a human observer by some ways and means. For example, a mercury-in-glass thermometer is an instrument, because it maintains a linear relationship between thermal expansion of mercury (prescribed property) and temperature (physical variable), and communicates this relationship to us through a graduated scale.

A generalized instrument consists of (i) a transducer, (ii) a signal conditioner and transmitter, and (iii) a display/recording device (Fig. 1.1).

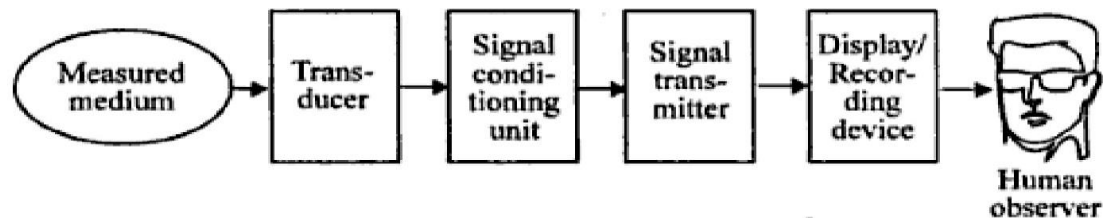


Fig. 1.1 A generalized instrument.

1.2.1 Transducer

A transducer senses the physical variable to be measured (i.e. measurand) and converts it to a suitable signal, preferably an electrical one.

One point has to be noted in this context. All transducers extract some energy from the measured medium which implies that the measurand is always disturbed by the measurement system. Therefore, *a perfect measurement is theoretically impossible*.

We will consider transducers in general in Chapter 2 and also study a few representative transducers for measurement of a few non-electrical quantities in Chapter 4.

1.2.2 Signal Conditioner and Transmitter

The signal generated by the transducer may need to be amplified, attenuated, integrated, differentiated, modulated, converted to a digital signal and so on. The signal conditioner performs one or more such tasks. Since electrical signals have distinct advantages in this respect, more so with the development of electronics, a signal conditioner is now basically an electronic gadget. We will, however, discuss only the basics of signal conditioning.

Signal transmitters are necessary for remote measurements. Remote measurements and control, called telemetry, constitute a highly-developed subject. We will exclude this topic from our consideration.

1.3 ■ ERRORS AND UNCERTAINTIES IN PERFORMANCE PARAMETERS

The various static performance parameters of the instruments are obtained by performing certain specified tests depending on the type of instrument, the nature of the application, etc. Some salient static performance parameters are periodically checked by means of a static calibration. This is accomplished by imposing constant values of 'known' inputs and observing the resulting outputs. Quite often, we experience difficulty in obtaining known constant values of the input quantity. Further, we also come across the following difficulties:

1. The change in sensitivity of instruments due to certain perturbations results in influencing all output values, generally equally by a particular quantity. These are caused due to worn out parts, effect of changes in the environment on the equipment or the user, etc.
2. Failure of the instrument to have the same output for repeated applications of any particular value of the input. This effect, i.e. the *scatter* in output values, within a given range, is caused due to *random* variations in the parameter or in the system of measurement.

No measurement can be made with perfect accuracy and precision. Therefore, it is instructive to know the various types of errors and uncertainties that are in general, associated with measurement system. Further, it is also important to know how these errors are propagated. This is because if an error is detected, then it can be eliminated or its effect can be accounted for in the form of a suitable correction. On the other hand, if an error goes unrecognised, then it would make experimental data unreliable.

1.3.1 Types of Errors

Error is defined as the difference between the measured and the true value (as per standard). The different types of errors can be broadly classified as follows.

Systematic or Cumulative Errors Such errors are those that tend to have the same magnitude and sign for a given set of conditions. Because the algebraic sign is the same, they tend to accumulate and hence are known as cumulative errors. Since such errors alter the instrument reading by a fixed magnitude and with same sign from one reading to another, therefore, the error is also commonly termed as *instrument bias*. These types of errors are caused due to the following:

Instrument errors Certain errors are inherent in the instrument systems. These may be caused due to poor design/construction of the instrument. Errors in the divisions of graduated scales, inequality of the balance arms, irregular springs tension, etc., cause such errors. Instrument errors can be avoided by (i) selecting a suitable instrument for a given application, (ii) applying suitable correction after determining the amount of instrument error, and (iii) calibrating the instrument against a suitable standard.

Environmental errors These types of errors are caused due to variation of conditions external to the measuring device, including the conditions in the area surrounding the instrument. Commonly occurring changes in environmental conditions that may affect the instrument characteristics are the effects of changes in temperature, barometric pressure, humidity, wind forces, magnetic or electrostatic fields, etc. For example, change in ambient temperature causes errors due to expansion of the measuring tape. Similarly, buoyant effect of the wind causes errors on weights of a chemical balance.

Loading errors Such errors are caused by the act of measurement on the physical system being tested. Common examples of this type are: (i) introduction of additional resistance in the circuit by the measuring milliammeter which may alter the circuit current by significant amount, (ii) an obstruction type flow meter may partially block or disturb the flow conditions and consequently the flow rate shown by the meter may not be same as before the meter installation, and (iii) introduction of a thermometer alters the

thermal capacity of the system and thereby changes the original state of the system which gives rise to loading error in the temperature measurement.

It may be noted that systematic errors can be eliminated or alternatively, a suitable correction can be applied by properly calibrating the instrument. Therefore, instrument calibrations become very necessary as the measurements play a dominant role in any experiment. Further, systematic errors can also be subdivided into static or dynamic errors. Static errors are caused due to limitations of the instruments as well as due to certain shortcomings in the measurement process. For example, a static error is introduced in the micrometer reading when excessive torque is applied on the shaft of the micrometer screw. Dynamic errors are caused in the measurements if the instrument is not responding fast enough to follow the changes in the measured variable.

Accidental or Random Errors These errors are caused due to random variations in the parameter or the system of measurement. Such errors vary in magnitude and may be either positive or negative on the basis of chance alone. Since these errors are in either direction, they tend to compensate one another. Therefore, these errors are also called *chance or compensating type of errors*. The presence of such errors is detected by a lack of consistency in the measured values when the same input is imposed repeatedly on the instrument. In a well-designed experiment very few random errors occur but they become important in a high accuracy work. The following are some of the main contributing factors to random error.

Inconsistencies associated with accurate measurement of small quantities The outputs of the instruments become inconsistent when very accurate measurements are being made. This is because when the instruments are built or adjusted to measure small quantities, the random errors (which are of the order of the measured quantities) become noticeable. For example, if one wishes to measure the weight of a bucket of water to the nearest kilogram, there would be no excuse of one observation differing from another, no matter how many times the measurements are made. However, if one attempts to determine the same weight to the nearest milligram, individual observations are sure to differ unless these are performed with extreme care and without prejudice.

Presence of certain system defects System defects such as large dimensional tolerances in mating parts and the presence of friction contribute to errors that are either positive or negative depending on the direction of motion. The former causes backlash error and the latter causes slackness in the meter bearings. One way of detecting and correcting such errors is to measure the quantity first while increasing and then decreasing the magnitude. This procedure is based on the *method of symmetry*.

Effect of unrestrained and randomly varying parameters Chance errors are also caused due to the effect of certain uncontrolled disturbances which influence the instrument output. Line voltage fluctuations, vibrations of the instrument supports, etc. are common examples of this type. The experimenter should try to reduce the influence of such randomly varying parameters to the minimum. But, in spite of this, there are always certain residual contributions due to these random perturbations.

Miscellaneous Type of Gross Errors There are certain other errors that cannot be strictly classified as either systematic or random as they are partly systematic and partly random. Therefore, such errors are termed *miscellaneous type of gross errors*. This class of errors is mainly caused by the following.

Personal or human errors These are caused due to the limitations in the human senses. For example, one may sometimes consistently read the observed value either high or low and thus introduce systematic errors in the results. While at another time one may record the observed value slightly differently than the actual reading and consequently introduce random error in the data. Therefore, it becomes necessary to exercise extreme care with mature and considered judgement in recording the observations so as to reduce such errors.

Errors due to faulty components/adjustments Sometimes there is a misalignment of moving parts, electrical leakage, poor optics, etc. in the measuring system. These may simultaneously cause, for example, zero shift coupled with zero drift which are systematic and random errors, respectively. In such cases, it becomes necessary to determine the magnitude of the systematic and random errors from the overall gross error. The procedure usually consists of repeating a measurement for a sufficiently large number of times by feeding a 'standard' signal to the instrument. The difference between the mean value of the signal and the standard signal gives the best estimate of systematic error. Further, the estimate of uncertainty which represents the random error in measurement is evaluated from the dispersion of data.

Improper application of the instrument Errors of this type are caused due to the use of instrument in conditions which do not conform to the desired design/operating conditions. For example, extreme vibrations, mechanical shock or pick-up due to electrical noise could introduce so much gross error as to mask the test information. In such cases it becomes necessary to stop the experiment until the disturbing elements causing the *chaotic* type of gross errors are eliminated.

1.3.2 Types of Uncertainties

In any experiment, the exactness of the measured values is affected by deviations caused by the usually associated errors, namely, systematic and random errors. The combined effect of these errors i.e., gross errors can be separated into systematic and random type components. Since systematic errors and the systematic component of gross errors are deterministic in nature, therefore, it is best to eliminate the effect of such errors by introducing a suitable correction factor in the experimental results by a proper calibration procedure. Now, the remaining random errors and the random component of gross errors in general, constitute the chief source of uncertainty in experiments. In fact, the term 'random' error is a misnomer, it should really be termed as '*degree/amount of uncertainty*' which is evaluated from the dispersion/scatter in the data. It is worth mentioning here that even though the magnitude of random type deviations as well as their algebraic sign vary from one observation to another, yet fortunately they follow a definite mathematical law called the normal or Gaussian distribution (Ch. 22). When the various uncertainties are distributed in such a predictable manner, they can be quantified so as to increase the reliability of the experiment.

In general, we come across the two types of uncertainties in measured quantities as discussed here.

External estimate of uncertainty U_E This is usually assessed from the knowledge of the experiment, the limitation of the apparatus, the instrument manufacturer's literature, etc. However, in the absence of the above information, as a thumb rule, the resolution that is the smallest confidently measurable input change is considered as the external estimate of uncertainty. For example, we give a true input of 100 V to a well-calibrated voltmeter which has a resolution of 0.1 V. The expected voltmeter reading would obviously be 100 V. Now, we increase or decrease the input voltage in the range of ± 0.1 V, which is equal to the resolution of the instrument. The voltmeter would still indicate 100 V as the instrument is incapable of registering a change up to or below the resolution of the instrument. Therefore, it would be reasonable to say, in this case, that the measured value of 100 V has the external estimate of uncertainty U_E equal to ± 0.1 V.

Internal estimate of uncertainty U_I This type of uncertainty is that which is inherent in the data itself and its quantitative assessment is termed as the internal estimate of uncertainty U_I . This occurs because an instrument may indicate a slightly different value every time a given input is fed to the instrument. In other words, we may say that the data is associated with scatter in values. The internal estimate of uncertainty, also termed as internal standard error, is estimated as follows:

1. A reasonably large number of data of a particular measurement is obtained. This data is termed as 'population' and it is assumed to include all possible values.
2. The population is broken up into small portions termed 'samples'. The samples are so selected that they have equitable distribution of all the possible measurements. In other words, the selected values have no bias and this process is known as random sampling.
3. The means and standard deviations of each of the samples are evaluated which are considered estimated true value and uncertainty respectively for the sample.
4. To obtain the best estimate of the mean value, the mean of sample means, which is in effect population mean, is calculated.
5. To obtain the overall estimate of uncertainty, the standard deviation of sample means is calculated

Alternatively, this value can also be obtained by calculating the combined estimate of individual uncertainties of the sample values. The value thus obtained is known as the *internal estimate of uncertainty or the internal standard error*. This has been shown to be equal to sample standard deviation divided by square root of the number of samples.

It may be noted that a highly precise instrument with excellent repeatability characteristics is usually associated with quite small value of U_1 . But, such instruments are usually costly. On the other hand, a coarse instrument, which may be less expensive, is generally associated with larger value of U_1 . This however could be reduced to any desired value by carrying out repeat measurements a sufficiently large number of times.

Generally, *any experiment is considered consistent if the external and internal estimates of uncertainties are of the same order of magnitude*. This criterion ensures minimum overall uncertainty in the experiment. However, if these estimates differ considerably, then the higher of the two is generally taken as uncertainty of the experiment.

1.4 ■ STATIC PERFORMANCE PARAMETERS

The definitions and brief descriptions of the various static performance parameters of the instruments are as follows.

1.4.1 Accuracy

Accuracy of a measuring system is defined as the closeness of the instrument output to the true value of the measured quantity (as per standards). However, in usual practice, it is specified as the percentage deviation or inaccuracy of the measurement from the true value. For example, if a chemical balance reads 1 g with an error of 10^{-2} g, the accuracy of the measurement would be specified as 1%.

Accuracy of the instrument mainly depends on the inherent limitations of the instrument as well as on the shortcomings in the measurement process. In fact, these are the major parameters that are responsible for systematic or cumulative errors. In other words, the accuracy of an instrument depends on the various systematic errors involved in the measurement process. For example, the accuracy of a common laboratory micrometer depends on instrument errors like zero error, errors in the pitch of screw, anvil shape, etc. and in the measurement process errors are caused due to temperature variation effect, applied torque, etc.

The accuracy of the instruments (which represents really its inaccuracy) can be specified in either of the following forms:

1. Percentage of true value

$$= \frac{\text{measured value} - \text{true value}}{\text{true value}} \times 100 \quad (1.1)$$

2. Percentage of full-scale deflection

$$= \frac{\text{measured value} - \text{true value}}{\text{maximum scale value}} \times 100 \quad (1.2)$$

It may be noted that *accuracy specification of the instrument as a percentage of full scale deflection (% of fsd) is less accurate than the percentage of true value (% of TV)*. For example, an error $\pm 1\%$ of full-scale deflection of a voltmeter having a range of 1000 V means that a true voltage of 100 V could be read from 90 to 110 V. However, as a percentage of true value, it would be read from 99 to 101 V.

1.4.2 Precision

Precision is defined as the ability of the instrument to reproduce a certain set of readings within a given accuracy. For example, if a particular transducer is subjected to an accurately known input and if the repeated read outs of the instrument lie within say $\pm 1\%$, then the precision or alternatively the precision error of the instrument would be stated as $\pm 1\%$. Thus, a highly precise instrument is one that gives the same output information, for a given input information when the reading is repeated a large number of times.

Precision of an instrument is in fact, dependent on the repeatability. The term repeatability can be defined as the ability of the instrument to reproduce a group of measurements of the same measured quantity, made by the same observer, using the same instrument, under the same conditions. As mentioned before, the deviations in repeatability or the inconsistencies in the measured values are caused due to random or accidental errors. Therefore, the precision of the instrument depends on the factors that cause random or accidental errors. As mentioned before, the extent of random errors or alternatively the precision of a given set of measurements can be quantified by performing the statistical analysis.

Accuracy Versus Precision It may be noted that accuracy represents the degree of correctness of the measured value with respect to the true value. On the other hand, precision represents degree of repeatability of several independent measurements of the desired input at the same reference conditions. As mentioned before, accuracy and precision involved in a measurement are dependent on the systematic and random errors, respectively. Therefore, in any experiment both the quantities have to be evaluated. The former is determined by proper calibration of the instrument and the latter by statistical analysis. However, it is instructive to note that *a precise measurement may not necessarily be accurate and vice versa*. To illustrate this statement we take the example of a person doing shooting practice on a target. He can hit the target with the following possibilities as shown in Fig. 2.2.

1. One possibility is that the person hits all the bullets on the target plate on the outer circle and misses the bull's eye [Fig. 2.2(a)]. This is a case of high precision but poor accuracy.
2. Second possibility is that the bullets are placed as shown in Fig. 2.2(b). In this case, the bullet hits are placed symmetrically with respect to the bull's eye but are not spaced closely. Therefore, this is case of good average accuracy but poor precision.
3. A third possibility is that all the bullets hit the bull's eye and are also spaced closely [Fig. 2.2(c)]. As is clear from the diagram, this is a case of high accuracy and high precision.
4. Lastly, if the bullets hit the target plate in a random manner as shown in Fig. 2.2(d), then this is a case of poor precision as well as poor accuracy.

Based on the above discussion, it may be stated that in any experiment the *accuracy of the observations can be improved but not beyond the precision of the apparatus.*

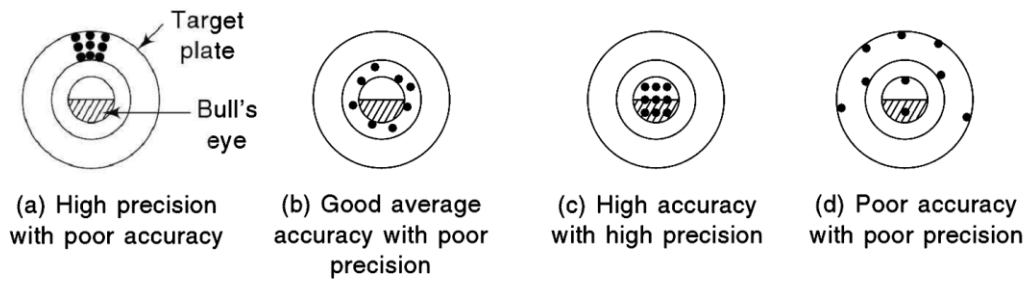


Fig. 2.2 Illustration of degree of accuracy and precision in a typical target shooting experiment