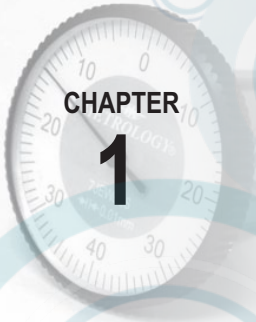
Metrology -

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CHAPTER

1 Basic Principles of Engineering Metrology

After studying this chapter, the reader will be able to

- understand the importance of metrology
- appreciate the significance of inspection
- appreciate the concepts of accuracy and precision
- explain the objectives of metrology and measurements
- understand the general measurement concepts
- elucidate the different sources and types of errors
- compare the different types of measurements

1.1 INTRODUCTION

The importance of metrology as a scientific discipline gained momentum during the industrial revolution. Continuing technological advancement further necessitated refinement in this segment. Metrology is practised almost every day, often unknowingly, in our day-to-day tasks. Measurement is closely associated with all the activities pertaining to scientific, industrial, commercial, and human aspects. Its role is ever increasing and encompasses different fields such as communications, energy, medical sciences, food sciences, environment, trade, transportation, and military applications. Metrology concerns itself with the study of measurements. It is of utmost importance to measure different types of parameters or physical variables and quantify each of them with a specific unit. Thus, measurement is an act of assigning an accurate and precise value to a physical variable. The physical variable then gets transformed into a measured variable. Meaningful measurements require common measurement standards and must be performed using them. The common methods of measurement are based on the development of international specification standards. These provide appropriate definitions of parameters and protocols that enable standard measurements to be made and also establish a common basis for comparing measured values. In addition, metrology is also concerned with the reproduction, conservation, and transfer of units of measurements and their standards. Measurements provide a basis for judgements about process information, quality assurance, and process control.

Design is one of the major aspects of all branches of engineering. A product/system comprising several elements has to be properly designed to perform the required (desired) function. In order to test whether functioning of the elements constituting the product/system meets the design expectation, and to finally assess the functioning of the whole system, measurements

are inevitable. Another associated aspect is to provide proper operation and maintenance of such a product/system. Measurement is a significant source for acquiring very important and necessary data about both these aspects of engineering, without which the function or analysis cannot be performed properly.

Hence, measurements are required for assessing the performance of a product/system, performing analysis to ascertain the response to a specific input function, studying some fundamental principle or law of nature, etc. Measurements contribute to a great extent to the design of a product or process to be operated with maximum efficiency at minimum cost and with desired maintainability and reliability.

Metrology helps extract high-quality information regarding the completion of products, working condition, and status of processes in an operational and industrial environment. A high product quality along with effectiveness and productivity is a must, in order to survive economically in this competitive global market. The task of attaining workpiece accuracy in modern industrial production techniques has gained much significance through constantly increasing demands on the quality of the parts produced. In order to achieve high product quality, metrology has to be firmly integrated into the production activity. Hence, metrology forms an inseparable key element in the process of manufacturing. This needs focus on the additional expense caused throughout the whole manufacturing process, due to worldwide competition. The quality of the products influences various production attributes such as continuity, production volume and costs, productivity, reliability, and efficiency of these products with respect to their application or their consumption in a diverse manner. Thus, it is desirable to use the resources in an optimal manner and strive to achieve cost reduction in manufacturing.

1.2 METROLOGY

Metrology literally means science of measurements. In practical applications, it is the enforcement, verification, and validation of predefined standards. Although metrology, for engineering purposes, is constrained to measurements of length, angles, and other quantities that are expressed in linear and angular terms, in a broader sense, it is also concerned with industrial inspection and its various techniques. Metrology also deals with establishing the units of measurements and their reproduction in the form of standards, ascertaining the uniformity of measurements, developing methods of measurement, analysing the accuracy of methods of measurement, establishing uncertainty of measurement, and investigating the causes of measuring errors and subsequently eliminating them.

not all measurement can be eliminated Ex: (Random error)

The word metrology is derived from the Greek word ‘metrologia’, which means measure. Metrology has existed in some form or other since ancient times. In the earliest forms of metrology, standards used were either arbitrary or subjective, which were set up by regional or local authorities, often based on practical measures like the length of an arm.

It is pertinent to mention here the classic statement made by Lord Kelvin (1824–1907), an eminent scientist, highlighting the importance of metrology: ‘When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge of it is of a meagre and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thought advanced to the stage of science.’

Another scientist Galileo (1564–1642) has clearly formulated the comprehensive goal of metrology with the following statement: 'Measure everything that is measurable and make measurable what is not so.'

Metrology is an indispensable part of the modern day infrastructure. In fact, it plays an important role in our lives, either directly or indirectly, in various ways. In this competitive world, economic success of most of the manufacturing industries critically depends on the quality and reliability of the products manufactured—requirements in which measurement plays a key role. It has become increasingly essential to conform to the written standards and specifications and mutual recognition of measurements and tests, to trade in national and international markets. This can be achieved by the proper application of measurement methods that enhance the quality of products and the productive power of plants.

Metrology not only deals with the establishment, reproduction, protection, maintenance, and transfer or conversion of units of measurements and their standards, but is also concerned with the correctness of measurement. In addition to encompassing different industrial sectors, it also plays a vital role in establishing standards in different fields that affect human beings, such as health sciences, safety, and environment. Hence, one of the major functions of metrology is to establish international standards for measurements used by all the countries in the world in both science and industry.

Modern manufacturing technology is based on precise reliable dimensional measurements. The term 'legal metrology' applies to any application of metrology that is subjected to national laws or regulations. There will be mandatory and legal bindings on the units and methods of measurements and measuring instruments. The scope of legal metrology may vary considerably from one country to another. The main objective is to maintain uniformity of measurement in a particular country. Legal metrology ensures the conservation of national standards and guarantees their accuracy in comparison with the international standards, thereby imparting proper accuracy to the secondary standards of the country. Some of the applications of legal metrology are industrial measurement, commercial transactions, and public health and human safety aspects.

A group of techniques employed for measuring small variations that are of a continuous nature is termed as 'dynamic metrology'. These techniques find application in recording continuous measurements over a surface and have obvious advantages over individual measurements of a distinctive character.

The metrology in which part measurement is substituted by process measurement is known as 'deterministic metrology'. An example of deterministic metrology is a new technique known as 3D error compensation by computer numerical control (CNC) systems and expert systems, leading to fully adaptive control. This technology is adopted in high-precision manufacturing machinery and control systems to accomplish micro and nanotechnology accuracies.

1.3 NEED FOR INSPECTION

Industrial inspection has acquired significance in recent times and has a systematic and scientific approach. Prior to the industrial revolution, craftsmen used to assemble the different parts by hand and, in the process, consumed a lot of time. They were entirely responsible for the quality of their products. Inspection was an integral function of production. Since the

industrial revolution, many new manufacturing techniques have been developed to facilitate mass production of components.

In modern manufacturing techniques, a product has to be disintegrated into different components. Manufacture of each of these components is then treated as an independent process.

F.W. Taylor, who has been acknowledged as the father of scientific management of manufacturing industry, created the modern philosophy of production and also the philosophy of production metrology and inspection. He decomposed a job into multiple tasks, thereby isolating the tasks involved in inspection from the production tasks. This culminated in the creation of a separate quality assurance department in manufacturing industries, which is assigned the task of inspection and quality control.

Inspection is defined as a procedure in which a part or product characteristic, such as a dimension, is examined to determine whether it conforms to the design specification. Basically, inspection is carried out to isolate and evaluate a specific design or quality attribute of a component or product. Industrial inspection assumed importance because of mass production, which involved interchangeability of parts. The various components that come from different locations or industries are then assembled at another place. This necessitates that parts must be so assembled that satisfactory mating of any pair chosen at random is possible. In order to achieve this, dimensions of the components must be well within the permissible limits to obtain the required assemblies with a predetermined fit. Measurement is an integral part of inspection. Many inspection methods rely on measurement techniques, that is, measuring the actual dimension of a part, while others employ the gauging method. The gauging method does not provide any information about the actual value of the characteristic but is faster when compared to the measurement technique. It determines only whether a particular dimension of interest is well within the permissible limits or not. If the part is found to be within the permissible limits, it is accepted; otherwise it is rejected. The gauging method determines the dimensional accuracy of a feature, without making any reference to its actual size, which saves time. In inspection, the part either passes or fails. Thus, industrial inspection has become a very important aspect of quality control.

Inspection essentially encompasses the following:

1. Ascertain that the part, material, or component conforms to the established or desired standard.
2. Accomplish interchangeability of manufacture.
3. Sustain customer goodwill by ensuring that no defective product reaches the customers.
4. Provide the means of finding out inadequacies in manufacture. The results of inspection are recorded and reported to the manufacturing department for further action to ensure production of acceptable parts and reduction in scrap.
5. Purchase good-quality raw materials, tools, and equipment that govern the quality of the finished products.
6. Coordinate the functions of quality control, production, purchasing, and other departments of the organizations.
7. Take the decision to perform rework on defective parts, that is, to assess the possibility of making some of these parts acceptable after minor repairs.
8. Promote the spirit of competition, which leads to the manufacture of quality products in bulk by eliminating bottlenecks and adopting better production techniques.

1.4 ACCURACY AND PRECISION

We know that accuracy of measurement is very important for manufacturing a quality product. *Accuracy* is the degree of agreement of the measured dimension with its true magnitude. It can also be defined as the maximum amount by which the result differs from the true value or as the nearness of the measured value to its true value, often expressed as a percentage. True value may be defined as the mean of the infinite number of measured values when the average deviation due to the various contributing factors tends to zero. In practice, realization of the true value is not possible due to uncertainties of the measuring process and hence cannot be determined experimentally. Positive and negative deviations from the true value are not equal and will not cancel each other. One would never know whether the quantity being measured is the true value of the quantity or not.

Precision is the degree of repetitiveness of the measuring process. It is the degree of agreement of the repeated measurements of a quantity made by using the same method, under similar conditions. In other words, precision is the repeatability of the measuring process. The ability of the measuring instrument to repeat the same results during the act of measurements for the same quantity is known as *repeatability*. Repeatability is random in nature and, by itself, does not assure accuracy, though it is a desirable characteristic. Precision refers to the consistent reproducibility of a measurement. Reproducibility is normally specified in terms of a scale reading over a given period of time. If an instrument is not precise, it would give different results for the same dimension for repeated readings. In most measurements, precision assumes more significance than accuracy. It is important to note that the scale used for the measurement must be appropriate and conform to an internationally accepted standard.

It is essential to know the difference between precision and accuracy. Accuracy gives information regarding how far the measured value is with respect to the true value, whereas precision indicates quality of measurement, without giving any assurance that the measurement is correct. These concepts are directly related to random and systematic measurement errors.

Figure 1.1 also clearly depicts the difference between precision and accuracy, wherein several measurements are made on a component using different types of instruments and the results plotted.

It can clearly be seen from Fig. 1.1 that precision is not a single measurement but is associated with a process or set of measurements. Normally, in any set of measurements performed by the same instrument on the same component, individual measurements are distributed around the mean value and precision is the agreement of these values with each other. The difference

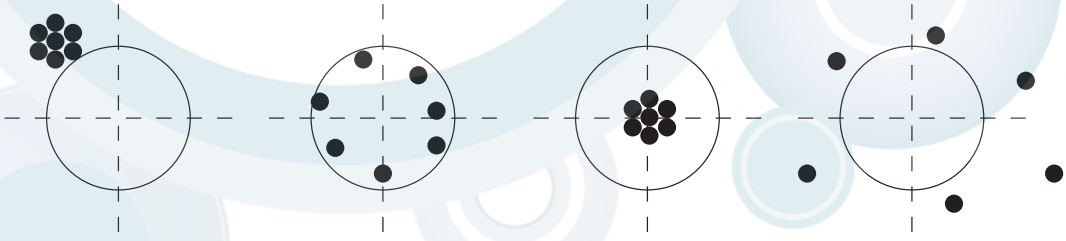


Fig. 1.1 Accuracy and precision (a) Precise but not accurate (b) Accurate but not precise (c) Precise and accurate (d) Not precise and not accurate

between the true value and the mean value of the set of readings on the same component is termed as an *error*. Error can also be defined as the difference between the indicated value and the true value of the quantity measured.

$$E = V_m - V_t$$

where E is the error, V_m the measured value, and V_t the true value.

The value of E is also known as the absolute error. For example, when the weight being measured is of the order of 1 kg, an error of ±2 g can be neglected, but the same error of ±2 g becomes very significant while measuring a weight of 10 g. Thus, it can be mentioned here that for the same value of error, its distribution becomes significant when the quantity being measured is small. Hence, % error is sometimes known as relative error. Relative error is expressed as the ratio of the error to the true value of the quantity to be measured. Accuracy of an instrument can also be expressed as % error. If an instrument measures V_m instead of V_t, then,

$$\% \text{ error} = \frac{\text{Error}}{\text{True value}} \times 100$$

Or

$$\% \text{ error} = \frac{V_m - V_t}{V_t} \times 100$$

Accuracy of an instrument is always assessed in terms of error. The instrument is more accurate if the magnitude of error is low. It is essential to evaluate the magnitude of error by other means as the true value of the quantity being measured is seldom known, because of the uncertainty associated with the measuring process. In order to estimate the uncertainty of the measuring process, one needs to consider the systematic and constant errors along with other factors that contribute to the uncertainty due to scatter of results about the mean. Consequently, when precision is an important criterion, mating components are manufactured in a single plant and measurements are obtained with the same standards and internal measuring precision, to accomplish interchangeability of manufacture. If mating components are manufactured at different plants and assembled elsewhere, the accuracy of the measurement of two plants with true standard value becomes significant.

In order to maintain the quality of manufactured components, accuracy of measurement is an important characteristic. Therefore, it becomes essential to know the different factors that affect accuracy. Sense factor affects accuracy of measurement, be it the sense of feel or sight. In instruments having a scale and a pointer, the accuracy of measurement depends upon the threshold effect, that is, the pointer is either just moving or just not moving. Since accuracy of measurement is always associated with some error, it is essential to design the measuring equipment and methods used for measurement in such a way that the error of measurement is minimized.

Two terms are associated with accuracy, especially when one strives for higher accuracy in measuring equipment: sensitivity and consistency. The ratio of the change of instrument indication to the change of quantity being measured is termed as *sensitivity*. In other words, it is the ability of the measuring equipment to detect small variations in the quantity being measured. When efforts are made to incorporate higher accuracy in measuring equipment, its sensitivity increases. The permitted degree of sensitivity determines the accuracy of the instrument. An instrument cannot

be more accurate than the permitted degree of sensitivity. It is very pertinent to mention here that unnecessary use of a more sensitive instrument for measurement than required is a disadvantage. When successive readings of the measured quantity obtained from the measuring instrument are same all the time, the equipment is said to be *consistent*. A highly accurate instrument possesses both sensitivity and consistency. A highly sensitive instrument need not be consistent, and the degree of consistency determines the accuracy of the instrument. An instrument that is both consistent and sensitive need not be accurate, because its scale may have been calibrated with a wrong standard. Errors of measurement will be constant in such instruments, which can be taken care of by calibration. It is also important to note that as the magnification increases, the range of measurement decreases and, at the same time, sensitivity increases. Temperature variations affect an instrument and more skill is required to handle it. *Range* is defined as the difference between the lower and higher values that an instrument is able to measure. If an instrument has a scale reading of 0.01–100 mm, then the range of the instrument is 0.01–100 mm, that is, the difference between the maximum and the minimum value.

1.4.1 Accuracy and Cost

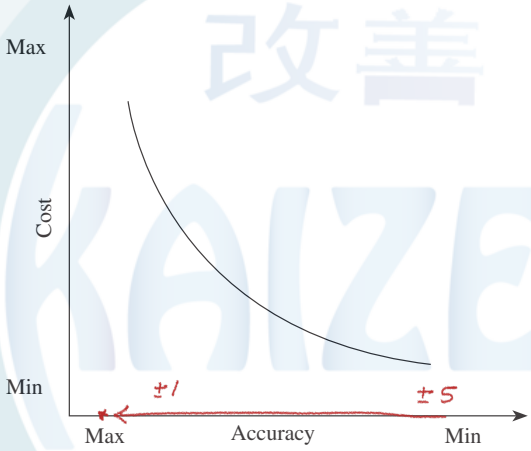


Fig. 1.2 Relationship of accuracy with cost

It can be observed from Fig. 1.2 that as the requirement of accuracy increases, the cost increases exponentially. If the tolerance of a component is to be measured, then the accuracy requirement will normally be 10% of the tolerance values. Demanding high accuracy unless it is absolutely required is not viable, as it increases the cost of the measuring equipment and hence the inspection cost. In addition, it makes the measuring equipment unreliable, because, as discussed in Section 1.4, higher accuracy increases sensitivity. Therefore, in practice, while designing the measuring equipment, the desired/required accuracy to cost considerations depends on the quality and reliability of the component/product and inspection cost.

1.5 OBJECTIVES OF METROLOGY AND MEASUREMENTS

From the preceding discussions, we know that accuracy of measurement is very important for the production of a quality product, and hence it is imperative to mention here that the basic objective of any measurement system is to provide the required accuracy at minimum cost. In addition, metrology is an integral part of modern engineering industry consisting of various departments, namely design, manufacturing, assembly, research and development, and engineering departments. The objectives of metrology and measurements include the following:

1. To ascertain that the newly developed components are comprehensively evaluated and designed within the process, and that facilities possessing measuring capabilities are available in the plant

2. To ensure uniformity of measurements
3. To carry out process capability studies to achieve better component tolerances
4. To assess the adequacy of measuring instrument capabilities to carry out their respective measurements
5. To ensure cost-effective inspection and optimal use of available facilities
6. To adopt quality control techniques to minimize scrap rate and rework
7. To establish inspection procedures from the design stage itself, so that the measuring methods are standardized
8. To calibrate measuring instruments regularly in order to maintain accuracy in measurement
9. To resolve the measurement problems that might arise in the shop floor
10. To design gauges and special fixtures required to carry out inspection
11. To investigate and eliminate different sources of measuring errors

1.6 GENERAL MEASUREMENT CONCEPTS

We know that the primary objective of measurement in industrial inspection is to determine the quality of the component manufactured. Different quality requirements, such as permissible tolerance limits, form, surface finish, size, and flatness, have to be considered to check the conformity of the component to the quality specifications. In order to realize this, quantitative information of a physical object or process has to be acquired by comparison with a reference. The three basic elements of measurements (schematically shown in Fig. 1.3), which are of significance, are the following:

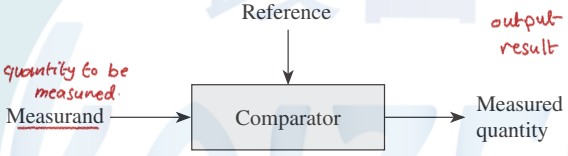


Fig. 1.3 Elements of measurement

1. *Measurand*, a physical quantity such as length, weight, and angle to be measured
2. *Comparator*, to compare the measurand (physical quantity) with a known standard (reference) for evaluation
3. *Reference*, the physical quantity or property to which quantitative comparisons are to be made, which is internationally accepted

All these three elements would be considered to explain the direct measurement using a calibrated fixed reference. In order to determine the length (a physical quantity called measurand) of the component, measurement is carried out by comparing it with a steel scale (a known standard).

1.6.1 Calibration of Measuring Instruments

It is essential that the equipment/instrument used to measure a given physical quantity is validated. The process of validation of the measurements to ascertain whether the given physical quantity conforms to the original/national standard of measurement is known as *traceability* of the standard. One of the principal objectives of metrology and measurements is to analyse the uncertainty of individual measurements, the efforts made to validate each measurement with a given equipment/instrument, and the data obtained from it. It is essential

that traceability (which is often performed by a calibration laboratory having conformity with a proven quality system with such standards) should disseminate to the consumers. Calibration is a means of achieving traceability. One of the essential aspects of metrology is that the results of measurements obtained should be meaningful. To accomplish this, calibration of any measuring system/instrument is very essential. Calibration is the procedure used to establish a relationship between the values of the quantities indicated by the measuring instrument and the corresponding values realized by standards under specified conditions. It refers to the process of establishing the characteristic relationship between the values of the physical quantity applied to the instrument and the corresponding positions of the index, or creating a chart of quantities being measured versus readings of the instrument. If the instrument has an arbitrary scale, the indication has to be multiplied by a factor to obtain the nominal value of the quantity measured, which is referred to as *scale factor*. If the values of the variable involved remain constant (not time dependent) while calibrating a given instrument, this type of calibration is known as *static calibration*, whereas if the value is time dependent or time-based information is required, it is called *dynamic calibration*. The relationship between an input of known dynamic behaviour and the measurement system output is determined by dynamic calibration.

The main objective of all calibration activities is to ensure that the measuring instrument will function to realize its accuracy objectives. General calibration requirements of the measuring systems are as follows: (a) accepting calibration of the new system, (b) ensuring traceability of standards for the unit of measurement under consideration, and (c) carrying out calibration of measurement periodically, depending on the usage or when it is used after storage.

Calibration is achieved by comparing the measuring instrument with the following: (a) a primary standard, (b) a known source of input, and (c) a secondary standard that possesses a higher accuracy than the instrument to be calibrated. During calibration, the dimensions and tolerances of the gauge or accuracy of the measuring instrument is checked by comparing it with a standard instrument or gauge of known accuracy. If deviations are detected, suitable adjustments are made in the instrument to ensure an acceptable level of accuracy. The limiting factor of the calibration process is repeatability, because it is the only characteristic error that cannot be calibrated out of the measuring system and hence the overall measurement accuracy is curtailed. Thus, repeatability could also be termed as the minimum uncertainty that exists between a measurand and a standard. Conditions that exist during calibration of the instrument should be similar to the conditions under which actual measurements are made. The standard that is used for calibration purpose should normally be one order of magnitude more accurate than the instrument to be calibrated. When it is intended to achieve greater accuracy, it becomes imperative to know all the sources of errors so that they can be evaluated and controlled.

1.7 ERRORS IN MEASUREMENTS

While performing physical measurements, it is important to note that the measurements obtained are not completely accurate, as they are associated with uncertainty. Thus, in order to analyse the measurement data, we need to understand the nature of errors associated with the measurements.

Therefore, it is imperative to investigate the causes or sources of these errors in measurement

systems and find out ways for their subsequent elimination. Two broad categories of errors in measurement have been identified: systematic and random errors.

1.7.1 Systematic or Controllable Errors

A systematic error is a type of error that deviates by a fixed amount from the true value of measurement. These types of errors are controllable in both their magnitude and their direction, and can be assessed and minimized if efforts are made to analyse them. In order to assess them, it is important to know all the sources of such errors, and if their algebraic sum is significant with respect to the manufacturing tolerance, necessary allowance should be provided to the measured size of the workpiece. Examples of such errors include measurement of length using a metre scale, measurement of current with inaccurately calibrated ammeters, etc. When the systematic errors obtained are minimum, the measurement is said to be extremely accurate. It is difficult to identify systematic errors, and statistical analysis cannot be performed. In addition, systematic errors cannot be eliminated by taking a large number of readings and then averaging them out. These errors are reproducible inaccuracies that are consistently in the same direction. Minimization of systematic errors increases the accuracy of measurement. The following are the reasons for their occurrence:

1. Calibration errors
2. Ambient conditions
3. Deformation of workpiece
4. Avoidable errors

Ex: Standard temp.
Ambient cond. at internationally accepted value of Standard temp = 20 C°

Calibration Errors

A small amount of variation from the nominal value will be present in the actual length standards, as in slip gauges and engraved scales. Inertia of the instrument and its hysteresis effects do not allow the instrument to translate with true fidelity. Hysteresis is defined as the difference between the indications of the measuring instrument when the value of the quantity is measured in both the ascending and descending orders. These variations have positive significance for higher-order accuracy achievement. Calibration curves are used to minimize such variations. Inadequate amplification of the instrument also affects the accuracy.

Ambient Conditions

It is essential to maintain the ambient conditions at internationally accepted values of standard temperature (20 °C) and pressure (760 mmHg) conditions. A small difference of 10 mmHg can cause errors in the measured size of the component. The most significant ambient condition affecting the accuracy of measurement is temperature. An increase in temperature of 1 °C results in an increase in the length of C25 steel by 0.3 µm, and this is substantial when precision measurement is required. In order to obtain error-free results, a correction factor for temperature has to be provided. Therefore, in case of measurements using strain gauges, temperature compensation is provided to obtain accurate results. Relative humidity, thermal gradients, vibrations, and CO_2 content of the air affect the refractive index of the atmosphere. Thermal expansion occurs due to heat radiation from different sources such as lights, sunlight, and body temperature of operators.

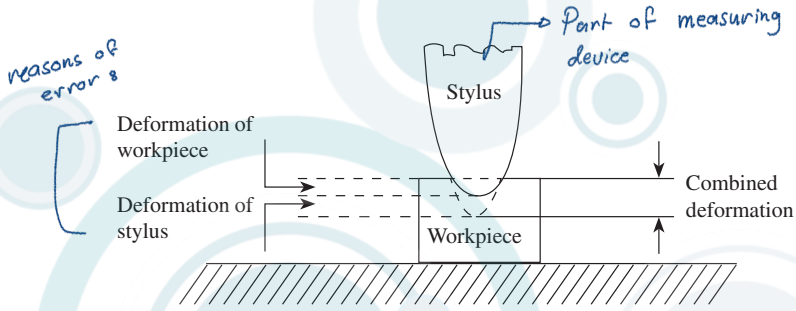


Fig. 1.4 Elastic deformation due to stylus pressure

Deformation of Workpiece

Any elastic body, when subjected to a load, undergoes elastic deformation. The stylus pressure applied during measurement affects the accuracy of measurement. Due to a definite stylus pressure, elastic deformation of the workpiece and deflection of the workpiece shape may occur, as shown in Fig. 1.4. The magnitude of deformation depends on the applied load, area of contact, and mechanical properties of the material of the given workpiece. Therefore, during comparative measurement, one has to ensure that the applied measuring loads are same.

Avoidable Errors

These include the following:

Datum errors Datum error is the difference between the true value of the quantity being measured and the indicated value, with due regard to the sign of each. When the instrument is used under specified conditions and a physical quantity is presented to it for the purpose of verifying the setting, the indication error is referred to as the datum error.

Reading errors These errors occur due to the mistakes committed by the observer while noting down the values of the quantity being measured. Digital readout devices, which are increasingly being used for display purposes, eliminate or minimize most of the reading errors usually made by the observer.

Errors due to parallax effect Parallax errors occur when the sight is not perpendicular to the instrument scale or the observer reads the instrument from an angle. Instruments having a scale and a pointer are normally associated with this type of error. The presence of a mirror behind the pointer or indicator virtually eliminates the occurrence of this type of error.

Effect of misalignment These occur due to the inherent inaccuracies present in the measuring instruments. These errors may also be due to improper use, handling, or selection of the instrument. Wear on the micrometer anvils or anvil faces not being perpendicular to the axis results in misalignment, leading to inaccurate measurements. If the alignment is not proper, sometimes sine and cosine errors also contribute to the inaccuracies of the measurement.

Zero errors When no measurement is being carried out, the reading on the scale of the instrument should be zero. A zero error is defined as that value when the initial value of a physical quantity indicated by the measuring instrument is a non-zero value when it should have actually been zero. For example, a voltmeter might read 1 V even when it is not under any electromagnetic influence. This voltmeter indicates 1 V more than the true value for all subsequent measurements made. This error is constant for all the values measured using the same instrument. A *constant error* affects all measurements in a measuring process by the same amount or by an amount proportional to the magnitude of the quantity being measured. For

example, in a planimeter, which is used to measure irregular areas, a constant error might occur because of an error in the scale used in the construction of standard or, sometimes, when an incorrect conversion factor is used in conversion between the units embodied by the scale and those in which the results of the measurements are expressed.

Therefore, in order to find out and eliminate any systematic error, it is required to calibrate the measuring instrument before conducting an experiment. Calibration reveals the presence of any systematic error in the measuring instrument.

1.7.2 Random Errors

Random errors provide a measure of random deviations when measurements of a physical quantity are carried out repeatedly. When a series of repeated measurements are made on a component under similar conditions, the values or results of measurements vary. Specific causes for these variations cannot be determined, since these variations are unpredictable and uncontrollable by the experimenter and are random in nature. They are of variable magnitude and may be either positive or negative. When these repeated measurements are plotted, they follow a normal or Gaussian distribution. Random errors can be statistically evaluated, and their mean value and standard deviation can be determined. These errors scatter around a mean value. If n measurements are made using an instrument, denoted by v_1, v_2, v_3, …, v_n, then arithmetic mean is given as

$$\bar{v} = \frac{v_1 + v_2 + v_3 \ldots \ldots \ldots v_n}{n}$$

and standard deviation σ is given by the following equation:

$$\sigma = \pm\sqrt{\sum \frac{\left(v - \bar{v}\right)^2}{n}}$$

Standard deviation is a measure of dispersion of a set of readings. It can be determined by taking the root mean square deviation of the readings from their observed numbers, which is given by the following equation:

$$\sigma = \pm\sqrt{\sum \frac{\left(v_1 - \bar{v}\right)^2 + \left(v_2 - \bar{v}\right)^2 + \ldots + \left(v_n - \bar{v}\right)^2}{n}}$$

Random errors can be minimized by calculating the average of a large number of observations. Since precision is closely associated with the repeatability of the measuring process, a precise instrument will have very few random errors and better repeatability. Hence, random errors limit the precision of the instrument. The following are the likely sources of random errors:

1. Presence of transient fluctuations in friction in the measuring instrument
2. Play in the linkages of the measuring instruments
3. Error in operator's judgement in reading the fractional part of engraved scale divisions
4. Operator's inability to note the readings because of fluctuations during measurement
5. Positional errors associated with the measured object and standard, arising due to small variations in setting

Figure 1.5 clearly depicts the relationship between systematic and random errors with respect to the measured value. The measure of a system's accuracy is altered by both systematic and random errors. Table 1.1 gives the differences between systematic and random errors.

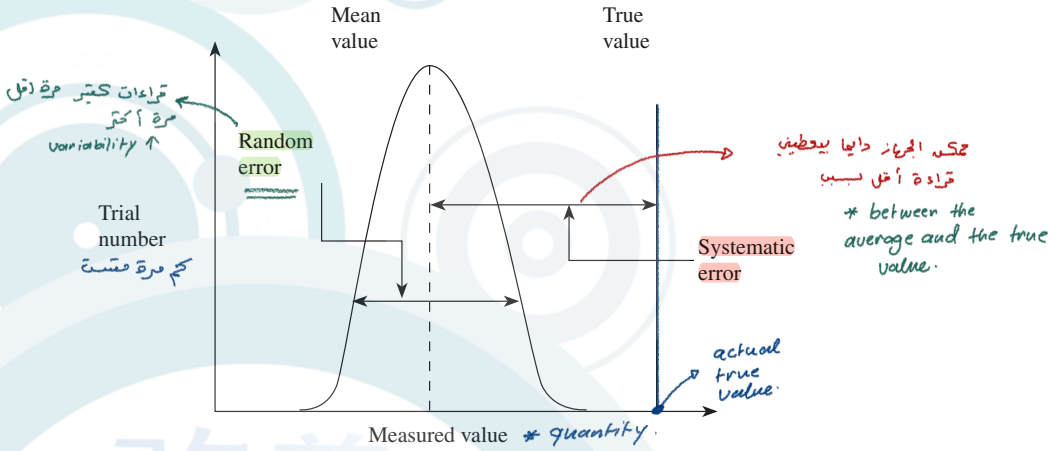


Fig. 1.5 Relationship between systematic and random errors with measured value

Table 1.1 Differences between systematic and random errors

Systematic error	Random error
Not easy to detect	Easy to detect
Cannot be eliminated by repeated measurements	Can be minimized by repeated measurements
Can be assessed easily	Statistical analysis required
Minimization of systematic errors increases the accuracy of measurement	Minimization of random errors increases repeatability and hence precision of the measurement
Calibration helps reduce systematic errors	Calibration has no effect on random errors
Characterization not necessary	Characterized by mean, standard deviation, and variance
Reproducible inaccuracies that are consistently in the same direction	Random in nature and can be both positive and negative

1.8 METHODS OF MEASUREMENT

When precision measurements are made to determine the values of a physical variable, different methods of measurements are employed. Measurements are performed to determine the magnitude of the value and the unit of the quantity under consideration. For instance, the length of a rod is 3 m, where the number, 3, indicates the magnitude and the unit of measurement is metre. The choice of the method of measurement depends on the required accuracy and the amount of permissible error. Irrespective of the method used, the primary objective is to

minimize the uncertainty associated with measurement. The common methods employed for making measurements are as follows:

Direct method In this method, the quantity to be measured is directly compared with the primary or secondary standard. Scales, vernier callipers, micrometers, bevel protractors, etc., are used in the direct method. This method is widely employed in the production field. In the direct method, a very slight difference exists between the actual and the measured values of the quantity. This difference occurs because of the limitation of the human being performing the measurement.

Indirect method In this method, the value of a quantity is obtained by measuring other quantities that are functionally related to the required value. Measurement of the quantity is carried out directly and then the value is determined by using a mathematical relationship. Some examples of indirect measurement are angle measurement using sine bar, measurement of strain induced in a bar due to the applied force, determination of effective diameter of a screw thread, etc.

Fundamental or absolute method In this case, the measurement is based on the measurements of base quantities used to define the quantity. The quantity under consideration is directly measured, and is then linked with the definition of that quantity.

Comparative method In this method, as the name suggests, the quantity to be measured is compared with the known value of the same quantity or any other quantity practically related to it. The quantity is compared with the master gauge and only the deviations from the master gauge are recorded after comparison. The most common examples are comparators, dial indicators, etc.

Transposition method This method involves making the measurement by direct comparison, wherein the quantity to be measured (V) is initially balanced by a known value (X) of the same quantity; next, X is replaced by the quantity to be measured and balanced again by another known value (Y). If the quantity to be measured is equal to both X and Y, then it is equal to

$$V = \sqrt{XY}$$

An example of this method is the determination of mass by balancing methods and known weights.

Coincidence method This is a differential method of measurement wherein a very minute difference between the quantity to be measured and the reference is determined by careful observation of the coincidence of certain lines and signals. Measurements on vernier calliper and micrometer are examples of this method.

Deflection method This method involves the indication of the value of the quantity to be measured directly by deflection of a pointer on a calibrated scale. Pressure measurement is an example of this method.

Complementary method The value of the quantity to be measured is combined with a known value of the same quantity. The combination is so adjusted that the sum of these two values is

equal to the predetermined comparison value. An example of this method is determination of the volume of a solid by liquid displacement.

Null measurement method In this method, the difference between the value of the quantity to be measured and the known value of the same quantity with which comparison is to be made is brought to zero.

Substitution method It is a direct comparison method. This method involves the replacement of the value of the quantity to be measured with a known value of the same quantity, so selected that the effects produced in the indicating device by these two values are the same. The Borda method of determining mass is an example of this method.

Contact method In this method, the surface to be measured is touched by the sensor or measuring tip of the instrument. Care needs to be taken to provide constant contact pressure in order to avoid errors due to excess constant pressure. Examples of this method include measurements using micrometer, vernier calliper, and dial indicator.

Contactless method As the name indicates, there is no direct contact with the surface to be measured. Examples of this method include the use of optical instruments, tool maker's microscope, and profile projector.

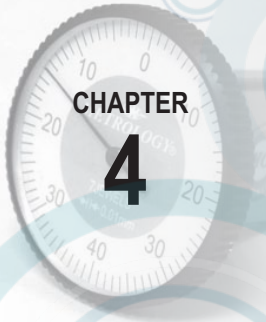
Composite method The actual contour of a component to be checked is compared with its maximum and minimum tolerance limits. Cumulative errors of the interconnected elements of the component, which are controlled through a combined tolerance, can be checked by this method. This method is very reliable to ensure interchangeability and is usually effected through the use of composite GO gauges. The use of a GO screw plug gauge to check the thread of a nut is an example of this method.

A QUICK OVERVIEW

- The importance and necessity of metrology have greatly increased with the industrial revolution, which emphasizes the importance of metrology in industries.
- Inspection is defined as a procedure in which a part or product characteristic, for example a dimension, is examined to determine whether it conforms to the design specification. Basically, inspection is carried out to isolate and evaluate a specific design or to measure the quality attribute of a component or product.
- We know that accuracy of measurement is very important in order to manufacture a quality product. *Accuracy* is the degree of agreement of the measured dimension with its true magnitude. It can also be defined as the maximum amount by which the result differs from true value.
- *Precision* is the degree of repetitiveness of the measuring process. It is the degree of agreement of the repeated measurements of a quantity made by using the same method, under similar conditions.
- The ability of the measuring instrument to repeat the same results during the act of measurements for the same quantity is known as *repeatability*.
- The difference between the true value and the mean value of the set of readings on the same component is termed as an *error*. Error can also

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* linear measurement devices : devices used to measure linear distances



CHAPTER 4

Linear Measurement

After studying this chapter, the reader will be able to

- understand the basic principles of design of linear measuring instruments
- explain the use of 'datum planes' in dimensional measurement
- appreciate the advantages offered by scaled instruments in contrast to a simple steel rule, and discuss the various applications and limitations of their variants
- elucidate the vernier family of instruments for linear measurement and read vernier instruments
- describe how Abbe's law applies to micrometer measurement
- explain how the micrometer principle has developed into a family of diverse instruments
- utilize the digital electronic instruments in linear measurement
- explain the use of slip gauges, and their manufacture and calibration

4.1 INTRODUCTION

In Chapter 2, the methods by which engineering standards of length are established were discussed. Both direct and indirect linear measuring instruments conform to these established standards of length and provide convenient means for making accurate and precise linear measurements. Vernier calliper and vernier micrometer are the most widely used linear measuring instruments in machine shops and tool rooms. Measuring instruments are designed either for line measurements (e.g., steel rule or vernier calliper) or for end measurements in order to measure the distance between two surfaces using an instrument (e.g., screw gauge). Callipers and dividers, which are also linear measurement devices, are basically *dimension transfer instruments*. They will not directly provide the measurement of length on a scale. Quality of measurement not only depends on the accuracy of these instruments, but also calls for application of certain simple principles to be followed during measurements. Illustrations are given throughout this chapter, especially on the latter issue, to highlight that care should be exercised for the proper use of linear measuring instruments.

Most people's first contact with linear measurement is with a steel rule or a tape measure. However, today's engineer has a choice of a wide range of instruments—from purely

* better devices in the accuracy

mechanically operated instruments to digital electronics instruments. One has to consider only the nature of application and cost of measurement to decide which instrument is the best for an application. This chapter covers a broad range of linear measurement instruments, from a simple steel rule to digital callipers and micrometers. However, many of these instruments, such as depth gauge and height gauge, need to be used with a datum to ensure accuracy of measurements. The foundation for all dimensional measurements is the 'datum plane', the most important ones being the surface plate and the V-block. Constructions of the surface plate and V-block are also explained with illustrations.

4.2 DESIGN OF LINEAR MEASUREMENT INSTRUMENTS

The modern industry demands manufacture of components and products to a high degree of dimensional accuracy and surface quality. Linear measurement instruments have to be designed to meet stringent demands of accuracy and precision. At the same time, the instruments should be simple to operate and low priced to make economic sense for the user. Proper attachments need to be provided to make the instrument versatile to capture dimensions from a wide range of components, irrespective of the variations in cross-sections and shapes. The following points highlight important considerations that have to be addressed in the design of linear measurement instruments:

1. The measuring accuracy of line-graduated instruments depends on the original accuracy of the line graduations. Excessive thickness or poor definition of graduated lines affects the accuracy of readings captured from the instrument.
2. Any instrument incorporating a scale is a suspect unless it provides compensation against wear.
3. Attachments can enhance the versatility of instruments. However, every attachment used along with an instrument, unless properly deployed, may contribute to accumulated error. Wear and tear of attachments can also contribute to errors. Use attachments when their presence improves reliability more than their added chance for errors decreasing it.
4. Instruments such as callipers depend on the feel of the user for their precision. Good quality of the instrument promotes reliability, but it is ultimately the skill of the user that ensures accuracy. Therefore, it is needless to say that proper training should be imparted to the user to ensure accurate measurements.
5. The principle of alignment states that the line of measurement and the line of dimension being measured should be coincident. This principle is fundamental to good design and ensures accuracy and reliability of measurements.
6. Dial versions of instruments add convenience to reading. Electronic versions provide digital readouts that are even easier to read. However, neither of these guarantees accuracy and reliability of measurements unless basic principles are adhered to.
7. One important element of reliability of an instrument is its *readability*. For instance, the smallest division on a micrometer is several times larger than that on a steel rule of say 0.1 mm resolution, which is difficult to read. However, the micrometer provides better least count, say up to 0.01 mm, compared to the same steel rule. Therefore, all other things being equal, a micrometer is more reliable than even a vernier scale. However, micrometers have a lesser range than verniers.

8. If cost is not an issue, digital instruments may be preferred. The chief advantage of the electronic method is the ease of signal processing. Readings may be directly expressed in the required form without additional arithmetic. For example, they may be expressed in either metric or British units, and can also be stored on a memory device for further use and analysis.
9. Whenever a contact between the instrument and the surface of the job being measured is inevitable, the contact force should be optimum to avoid distortion. The designer cannot leave the fate of the instrument on the skill of the user alone. A proper device like a *ratchet stop* can limit the contact force applied on the job during measurements, thereby avoiding stress on the instrument as well as distortion of the job.

4.3 SURFACE PLATE

In Section 4.2, we understood that every linear measurement starts at a reference point and ends at a measured point. This is true when our basic interest is in measuring a single dimension, length in this case. However, the foundation for all dimensional measurements is the 'datum plane', the most important one being the surface plate. A surface plate is a hard, solid, and horizontal flat plate, which is used as the reference plane for precision inspection, marking out, and precision tooling set-up (Fig. 4.1). Since a surface plate is used as the datum for all measurements on a job, it should be finished to a high degree of accuracy. It should also be robust to withstand repeated contacts with metallic workpieces and not be vulnerable to wear and tear.

The history of surface plates can be traced to the early 19th century when Richard Robert invented the planer in 1817, which was presumably the first machine tool that used a flat surface. He showed a way of duplicating flat surfaces with a high degree of accuracy, and the world of sliding motions and flat surfaces was born. However, the surface plates used by Roberts were of quite low accuracy compared to today's standards. One should credit the contribution of Sir Joseph Whitworth, a leading name in metrology, who recognized the lack of understanding of the concept of flatness at that time and devised a methodology in the year 1840 for generating a flat surface by the 'three-plate method'. This method is being used even today to manufacture surface plates, although better and modern methods of fabricating surface plates are becoming increasingly popular. In this method, three cast iron plates with ribbed construction (for rigidity) are rough machined along their edges and top surfaces. The plates are kept in the open for normalizing for about a year. Natural changes in temperature relieve the internal stresses. The plates are then finish-machined to a high degree of accuracy and are marked #1, #2, and #3, and applied with a coating of Prussian blue. In a six-step process, the surfaces of two of the plates are placed in contact in a particular order and the blued portions are scraped. The pairing of the plates is varied in a pre-planned sequence, which ensures that all three surfaces match to a high degree, thereby ensuring accurate flat surfaces.

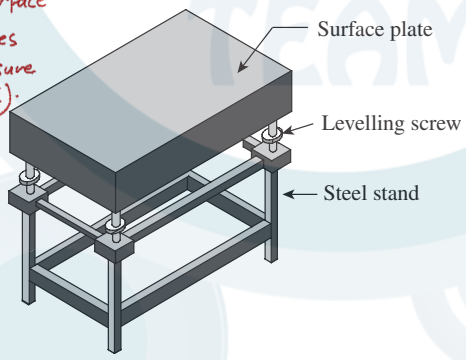


Fig. 4.1 Surface plate

The surface plates are made either from cast iron or from granite. Even though granite surface plates are perceived to be superior, cast iron surface plates are still in wide use. In fact, a cast iron surface plates is used as a tool for lapping granite surface plates to the required degree of accuracy. Cast iron allows itself to be impregnated with the lapping media over a large flat surface. In the following paragraphs, we will look into the construction and use of cast iron and granite surface plates in greater detail.

Cast Iron Surface Plates

Despite a drop in their usage, cast iron surface plates still retain popularity as surface masters. They are made of either plain or alloyed close-grained cast iron, reinforced with ribs to provide strength against bending or buckling. IS2285-1991 specifies the composition, size, and cross-sectional details of ribs and thickness of plates. The plates are manufactured in three grades, namely grade 0, grade I, and grade II. While grade 0 and grade I plates are hand scraped to achieve the required degree of flatness, grade II plates are precision machined to the required degree of accuracy. Table 4.1 illustrates some of the standard sizes of surface plates as per IS 2285-1991.

Table 4.1 Cast iron surface plate specifications as per IS 2285-1991

Size (mm)	Maximum deviation from flatness in microns			Approximate weight (kg)
	Grade 0	Grade I	Grade II	
300 × 300	4	7	15	21
400 × 400	4.5	9	17	50
450 × 300	4	8	16	39
450 × 450	4.5	9	18	62
600 × 450	5	10	20	79
630 × 400	5	10	20	96
600 × 600	5	10	20	128
630 × 630	5	10	21	156
900 × 600	6	12	23	204
1500 × 1200	8	16	33	986

Smaller-size plates are usually provided with a handle. All surface plates need to be provided with protective covers when not in use. Fabricated heavy angle iron stands with levelling screws provide convenient working height for surface plates. As per the proven practice devised by Sir Whitworth, surface plates are fabricated in sets of three. Cast iron is dimensionally more stable over time compared to granite plates. Unlike granite, it also has uniform optical properties with very small light penetration depth, which makes it a favourable material for certain optical applications. One significant drawback of cast iron is its higher coefficient of thermal expansion, which makes it unsuitable for applications involving large variations in temperature.

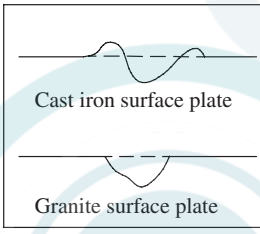


Fig. 4.2 Comparison between CI and granite surfaces

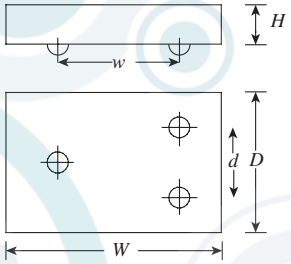


Fig. 4.3 Dimension parameters used in Table 4.2

Granite Surface Plates

In recent times, granite has replaced cast iron as the preferred material for surface plates. Most surface plates are made of black granite, while pink granite is the next preferred choice. Granite has many advantages over cast iron. Natural granite that is seasoned in the open for thousands of years is free from warp age or deterioration. It is twice as hard as cast iron and not affected by temperature changes. It is not vulnerable to rusting and is non-magnetic. As shown in Fig. 4.2, it is free from burrs or protrusions because of its very fine grain structure.

Table 4.2 lists some of the standard sizes of surface plates as per IS 2285-1991. Figure 4.3 illustrates the meaning of dimension parameters used in Table 4.2. The plates are manufactured in three grades, namely grade 00, grade 0, and grade 1. Flatness for grade 00 surface plates range from 0.002 to 0.007 mm, whereas that for grade 0 plates varies from 0.003 to 0.014 mm. Grade 1 plate is the coarsest, with flatness ranging from 0.005 to 0.027 mm.

Table 4.2 Sizes of granite surface plates as per IS 2285-1991

Grade	S. no.	Dimensions $W \times D \times H$ (mm)	Flatness (mm)	w (mm)	d (mm)	Mass (kg)
00	1	300 × 300 × 100	0.002	240	240	27
	2	450 × 300 × 100	0.002	390	240	40
	3	750 × 500 × 130	0.003	630	420	146
	4	1500 × 1000 × 200	0.004	1100	700	900
	5	3000 × 2000 × 500	0.007	2000	1500	9000
0	1	300 × 300 × 100	0.003	240	240	27
	2	450 × 300 × 100	0.003	390	240	40
	3	750 × 500 × 130	0.005	630	420	146
	4	1500 × 1000 × 200	0.008	1100	700	900
	5	3000 × 2000 × 500	0.014	2000	1500	9000
1	1	300 × 300 × 100	0.005	240	240	27
	2	450 × 300 × 100	0.006	390	240	40
	3	750 × 500 × 130	0.009	630	420	146
	4	1500 × 1000 × 200	0.016	1100	700	900
	5	3000 × 2000 × 500	0.027	2000	1500	9000

Glass Surface Plates

Glass is an alternative material for surface plates. It was used during World War II when material and manufacturing capacity were in short supply. Glass can be ground suitably and has the benefit that it chips rather than raising a burr, which is a problem in cast iron surface plates.

→ while the former is convenient for clamping the job onto the V-block, so that measurements can be made accurately, the latter has a magnetic base.

4.4 V-BLOCKS

used in the linear & angular measurements

V-blocks are extensively used for inspection of jobs with a circular cross section. The major purpose of a V-block is to hold cylindrical workpieces to enable measurement. The cylindrical surface rests firmly on the sides of the 'V', and the axis of the job will be parallel to both the base and the sides of the V-block. Generally, the angle of the V is 90°, though an angle of 120° is preferred in some cases. It is made of high-grade steel, hardened above 60 Rc, and ground to a high degree of precision. V-blocks are manufactured in various sizes ranging from 50 to 200 mm. The accuracy of flatness, squareness, and parallelism is within 0.005 mm for V-blocks of up to 150 mm length, and 0.01 mm for those of length between 150 and 200 mm (Fig. 4.4).

V-blocks are classified into two grades, grade A and grade B, according to IS: 2949-1964, based on accuracy. Grade A V-blocks have minimum departure from flatness (up to 5 µm for 150 mm length) compared to grade B V-blocks.

There are many variants of V-blocks, such as V-blocks with clamp, magnetic V-block, and cast iron V-block. Figure 4.5 illustrates a V-block with a stirrup clamp. It is convenient for clamping the job onto the V-block, so that measurements can be made accurately. Another popular type of V-block is the magnetic V-block, shown in Fig. 4.6. The magnetic base sits on a flat surface, preferably on a surface plate. The base and two sides are energized for gripping onto a flat surface and a 'vee'slot enables the device to grip the job firmly with a circular cross section. A push-button control turns the permanent magnetic field on and off, thereby enabling the attachment or detachment of the V-block to a flat surface. All three magnetic surfaces are carefully ground and, when switched on, all three magnetic surfaces are activated simultaneously. Magnetic V-blocks are used in tool rooms for drilling and grinding round jobs.

4.5 GRADUATED SCALES

only linear measurement device.

accuracy ↑ ⇒ cost ↑

We often use the words 'rule' and 'scale' to mean the simple devices that we have been using since primary-school geometry class. However, there is a clear difference in the actual meaning of these two familiar words. A scale is graduated in *proportion* to a unit of length. For example,

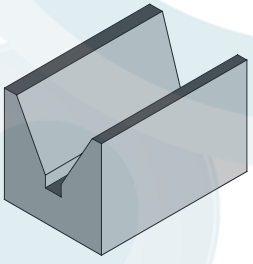


Fig. 4.4 V-block

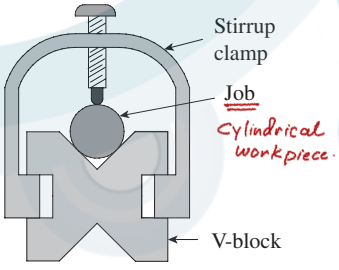
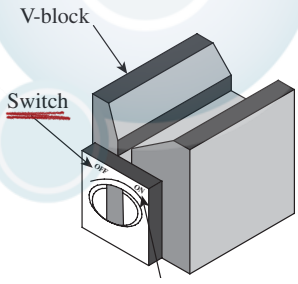


Fig. 4.5 V-block with a stirrup clamp



يشغل المغناطيس ما بين الشغلة و surface plate.

Fig. 4.6 Magnetic V-block

* V-block could be used to find the center of cylindrical workpiece

the divisions in an architect's scale, illustrated in Fig. 4.7, represent feet and inches, while the plumber's scale would have divisions in terms of 1/32th or 1/64th of an inch. The divisions of a rule, on the other hand, are the unit of length, its divisions, and its multiples. Typically, the rules with which we are familiar have graduations (in centimetres, millimetres, or inches) and their decimal divisions throughout the length.

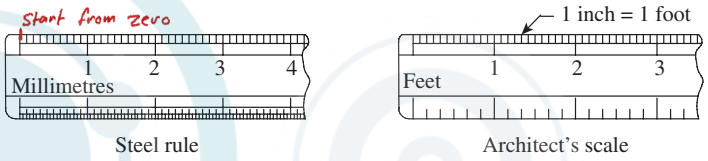


Fig. 4.7 Illustration of the difference between a rule and a scale

Steel rules are most popular in metrology applications since they are more accurate and durable compared to rules made from other materials such as wood or plastic. While rigid rules can be used for laying out lines on a job, flexible steel rules can also be used to measure surfaces with circular profiles. Steel rules are either stamped or cut from a roll of spring steel. The graduations are photo-engraved and tempered with satin chrome finish for good readability. The ruler can be 150, 300, 500, or 1000 mm long; 19 or 25 mm wide; and 1. mm thick. The finer sub-divisions may be marked either throughout the length of the scale or in only a part of its length.

The use of steel rule requires consideration of the relationship between the reference point and the measured point. Figure 4.8 illustrates the preferred way of choosing the reference point for making a measurement. A graduated line on the rule, rather than an edge of the rule, is selected as the reference point. This method improves the accuracy of measurement considerably, even though a little effort is required to align carefully, the reference and measured points. It is recommended not to use the edge of the rule as the reference point, as the edge is subjected to wear and tear and worn-out corners may contribute to error in measurements. Sometimes an attachment such as a hook or a knee is used to facilitate measurement, as shown in Fig. 4.9.

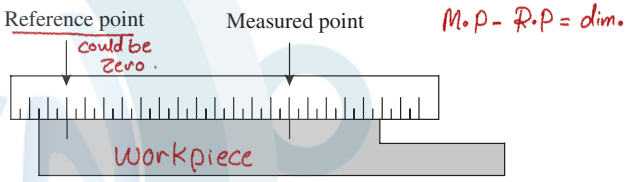


Fig. 4.8 Illustration of reference and measured points

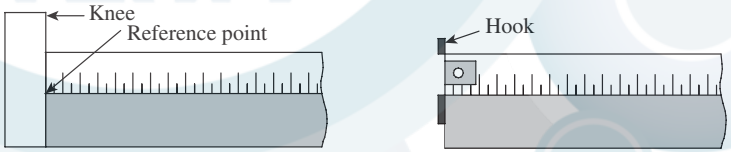


Fig 4.9 Correct ways of using a rule with attachments

4.5.1 Errors in Measurements

Steel rules are often used on the manufacturing shop floors for making measurements. Even though the least count of rules is limited to 1 mm or at the most to 0.5 mm, the user should

never be lax in the usage of any measuring device, however simple or trivial it may be. Therefore, one should be aware of the two common errors that can creep up in measurements involving rules. The first one is an inherent error because of poor quality of the rule. This can be attributed to either poor quality of the material of the rule or poor workmanship in the manufacture of the rule. One can avoid this by purchasing a good-quality rule from a standard vendor.

The second error may creep up because of wrong usage of a rule and the observational error. The rule should be properly aligned with the job being measured, ensuring that the reference and measured points are set accurately. The rule should not be twisted or bent in the process of measurement. The major observational error occurs because of parallax error. This is illustrated in Fig. 4.10. Parallax is the apparent shift in the position of an object caused by the change of position of the observer. If an observer views the scale along the direction B or C, the line of sight would be such that there is an apparent shift in the recorded reading by a division or two, as apparent from Fig. 4.10. The more the shift of the eye, from a vertical position right above the measured point, the more pronounced the error. It is needless to say that parallax error can be avoided if the observer recognizes this typical error and takes care to align his/her eyesight in the direction A, shown in Fig. 4.10.

Steel rules come in various sizes and shapes, depending upon the requirements of the component being measured. Accordingly, there are narrow rules, flexible fillet rules, short rules with holders, angle rules, measuring tapes, pocket tapes, and so on (Fig. 4.11). Narrow rules, fillet rules, and angle rules are used for measuring the inside of small holes, narrow slots, and grooves. Short rules with holders are convenient for measuring within recesses. Short rule is an extension of steel rule and obeys the same principle For very precise measurements, temperature expansion and contraction must be considered.

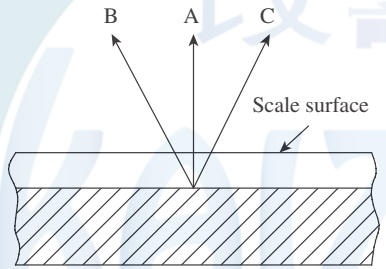
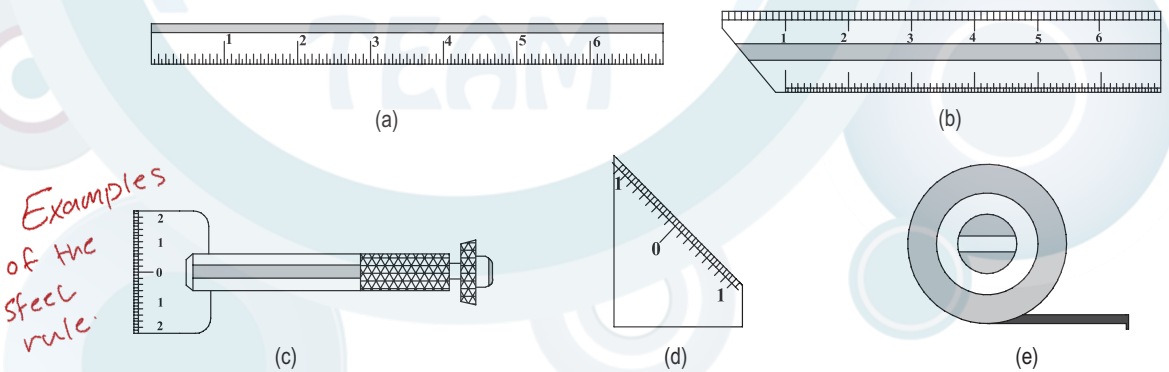


Fig. 4.10 Parallax error that can be minimized by direct eye measurements



Examples of the steel rule

Fig. 4.11 Types of steel rules (a) Narrow tempered steel rule (b) Flexible fillet rule (c) Short rule with holder (d) Angle rule (e) Steel measuring tape

للمناطق الصغيرة صعب نوصل

4.6 SCALED INSTRUMENTS

Rules are useful for many shop floor measurements. However, measurements of certain components require some mechanical means to either hold the measuring device steadily against the component being measured or capture the reading, which can be read at leisure. Another important advantage of a scaled instrument is that the least count of measurement can be improved greatly compared to an ordinary steel rule. Most of the modern scaled instruments provide digital display, which comes with a high degree of magnification. Measurements can be made up to micron accuracy. This section presents three scaled instruments, namely depth gauge, combination set, and callipers, which are necessary accessories in a modern metrology laboratory.

4.6.1 Depth Gauge

Depth gauge is the preferred instrument for measuring holes, grooves, and recesses. It basically consists of a graduated rod or rule, which can slide in a T-head (simply called the head) or stock. The rod or rule can be locked into position by operating a screw clamp, which facilitates accurate reading of the scale. Figure 4.12 illustrates a depth gauge, which has a graduated rule to read the measurement directly. The head is used to span the shoulder of a recess, thereby providing the reference point for measurement. The rod or rule is pushed into the recess until it bottoms. The screw clamp helps in locking the rod or rule in the head. The depth gauge is then withdrawn, and reading is recorded in a more convenient position. Thus, depth gauge is useful for measuring inaccessible points in a simple and convenient manner.

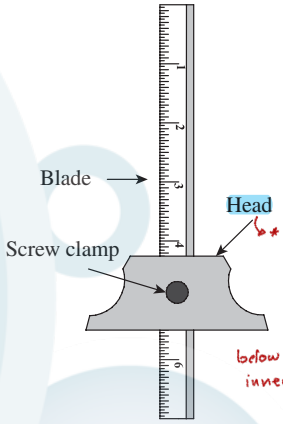


Fig. 4.12 Depth gauge

As already pointed out, either rods or rules can be used in depth gauges for the purpose of measurement. Although a slender rod can easily transfer measurements from narrow and inaccessible holes and recesses, the instrument cannot directly display the reading. One has to use another rule to measure the length of the protruded rod and record the measurement. This may lead to errors in measurements and reduce the reliability of the instrument. To overcome this problem, a graduated rod can be used, which can indicate the measurement directly. However, it is somewhat difficult to read graduations from a slender rod. Therefore, a narrow flat scale is the preferred choice for depth gauges. The rule is often referred to as the blade and is usually 150 mm long. The blade can accurately read up to 1 or ½ mm.

As already pointed out, the head is used to span the shoulder of a recess, thereby providing the reference point for measurement. This is illustrated in the rod-type depth gauge shown in Fig. 4.13. The end of the rod butts against the end surface to provide the measured point. Whenever depth needs to be measured, the projected length of the rod from the head is made very less. The lower surface of the head is firmly held against the job to ensure accurate location of the measured point. Now the rod is lowered until it butts against the surface of the job, thereby marking the measured point. The screw clamp is tightened, the instrument is slowly taken out, and the depth of the hole is read in a convenient position. This method is preferred

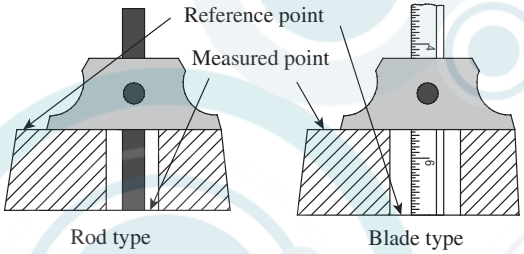


Fig. 4.13 Measured and reference points in depth gauges

for narrow recesses and holes. To summarize, the depth gauge is first positioned against the reference point, followed by the capture of the measured point in order to complete the measurement process.

Sometimes, it becomes necessary to alter the reference and measured points to suit the requirement, as illustrated by the blade-type depth gauge in Fig. 4.13. If the hole is large enough for visually positioning the blade of the depth gauge, the preferred method is to first locate the end of the blade against the lower surface of the hole. The blade is extended from the head, the instrument is brought close to the job, and the end of the blade is butted against the lower surface of the hole. This establishes the reference point for measurement. Now, the head is lowered and the lower surface of the head is made to butt against the top of the job, as shown in Fig. 4.10. The surface of the head provides the measured point. The screw clamp is now tightened and the measurement recorded.

Although depth gauge provides an easy and convenient method for measuring depths of holes and recesses, it has the following limitations:

1. The job size is limited by the width of the head of the depth gauge. Usually, the maximum width of the hole that can be spanned is about 50 mm.
2. The base of the head should be perpendicular to the line of measurement. Otherwise, the line of measurement will be skewed, resulting in erroneous readings.
3. The end of the blade must butt against the desired reference. This will be rather difficult to achieve, especially in blind holes.
4. The end of the blade and the lower surface of the head are always in contact with the job being measured. Therefore, these surfaces will undergo wear and tear. The instrument should be periodically checked for accuracy and replaced if the wear amounts to one graduation line of the instrument.

4.6.2 Combination Set

A combination set has three devices built into it: a combination square comprising a square head and a steel rule, a protractor head, and a centre head. While the combination square can be used as a depth or height gauge, the protractor head can measure the angles of jobs. The centre head comes in handy for measuring diameters of jobs having a circular cross section. The combination set is a useful extension of steel rule. This non-precision instrument is rarely used in any kind of production inspection. However, it is frequently used in tool rooms for tool and die making, pattern making, and fabrication of prototypes. It is a versatile and interesting instrument that has evolved from a try-square, which is used for checking squareness between two surfaces.

The graduated steel rule is grooved all along its length. The groove enables the square head to be moved along the length of the rule and fixed at a position by tightening the clamp screw provided on the square head. The square head along with the rule can be used for measuring heights and depths, as well as inside and outside squaring operations. The blade of the graduated

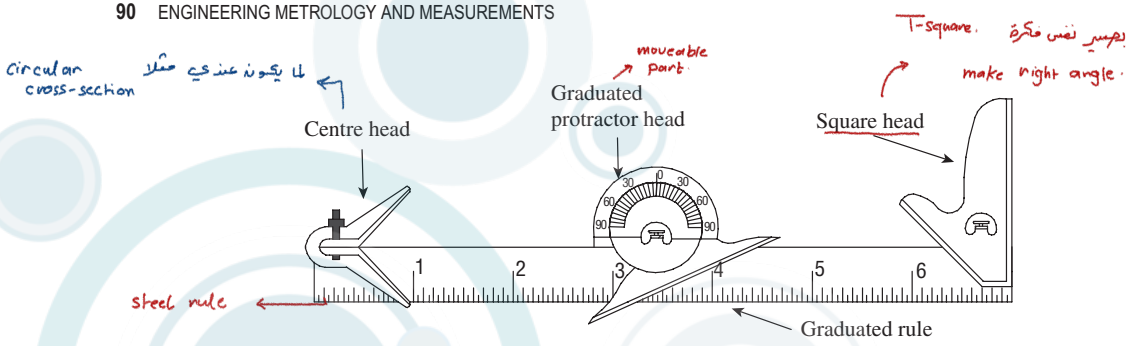


Fig. 4.14 Combination set

protractor head can be swivelled to any angle, which enables the measurement of angles on jobs. The protractor can also be moved along the scale and fixed at a convenient point. Protractors of some combination sets are provided with a spirit level for the purpose of levelling a surface. The centre head attachment is used with the rule to locate the centre of bar stocks. The illustration in Fig. 4.14 shows how each of these attachments are integrated in the combination set.

Square Head

The square head along with the graduated rule on the combination set provides an easy way of measuring heights and depths. While the square head provides a right angle reference, the rule provides a means for directly taking the readings. However, a primary requirement is that the square head can be used only against a flat reference surface. Figure 4.15 illustrates a typical method of measuring height using the combination set. The square head is firmly held against a flat surface of the job, and the rule is lowered until it touches the reference point at the bottom of the job, as shown in the figure. The rule can be locked in this position, and the reading noted down in a convenient position. Attachments are available to mark the measured point with reference to the end of the steel rule. The range of measurement can also be extended by using attachments. In some instruments, the square head is provided with a spirit level, which can be used to test the surfaces for parallelism. A scribing point is provided at the rear of the base in some instruments for scribing purposes.

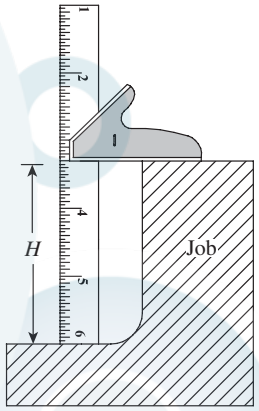


Fig. 4.15 Combination square as a height gauge

Protractor Head

Figure 4.16 illustrates the use of the protractor head on the combination set. This head comprises a rotatable turret within a stock. The turret has an angular scale graduated in degrees. Similar to the square head, the protractor head can also slide along the rule. The blade of the protractor is held firmly against the job and the angle can be directly read from the scale. A spirit level provided on the protractor head can be used for the purpose of levelling a surface. The protractor can also be used to determine the deviation of angle on the job from the desired one. The protractor is first set to the correct angle and locked in position. Now it is held against

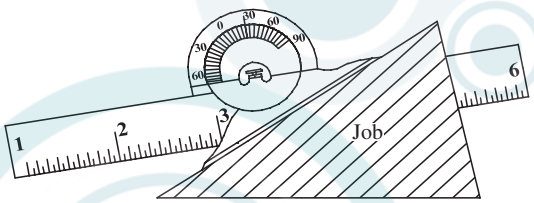


Fig. 4.16 Use of a protractor head for angle measurement

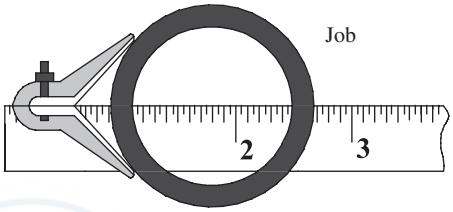


Fig. 4.17 Use of a centre head for the measurement of diameter

the surface of the job for which angle is to be measured. Any deviation from the desired angle can be checked by inserting angle gauges (feeler gauges) in the gap between the blade of the protractor and the job.

Centre Head

The centre head attachment is used along with the steel rule to locate the centre of a bar stock or a circular job. It can be seen from Fig. 4.17 that one edge of the steel rule bisects the V-angle of the centre head. Therefore, it lies on the centre line of any circular job held against the centre head. The diameter of the job can be directly read on the graduated scale, which is useful for marking the centre of the job by using a scriber. The V between the two blades of the centre head facilitates accurate positioning of circular jobs, which greatly improves measurement accuracy when compared to taking readings directly using a rule held against the job. The latter method is completely manual and depends on the skill of the person taking the reading, and therefore is highly prone to error.

Combination sets are available in various sizes. The length of the steel rule ranges from 150 to 600 mm. The scales are graduated in mm and 0.5 mm, and the graduations are available on both sides of the scale. Considering two sets of graduations on one side of the rule, it is possible to have four scales with different graduation schemes and least count. This enhances the versatility of the instrument considerably.

4.6.3 Callipers

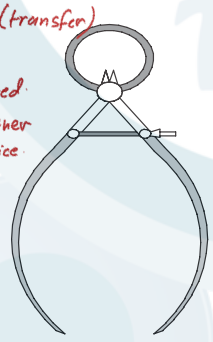


Fig. 4.18 Callipers, the original transfer instruments

There are many jobs whose dimensions cannot be accurately measured with a steel rule alone. A typical case in point is a job with a circular cross section. An attempt to take measurement using a steel rule alone will lead to error, since the steel rule cannot be positioned diametrically across the job with the required degree of accuracy. One option is to use the combination set. However, callipers are the original transfer instruments to transfer such measurements on to a rule (Fig. 4.18). They can easily capture the diameter of a job, which can be manually identified as the maximum distance between the legs of the calliper that can just slide over the diameter of the job. Even though callipers are rarely used in production inspection, they are widely used in tool room and related work.

Busch defines *callipers as instruments that physically duplicate the separation between the reference point and measured point of any dimension*

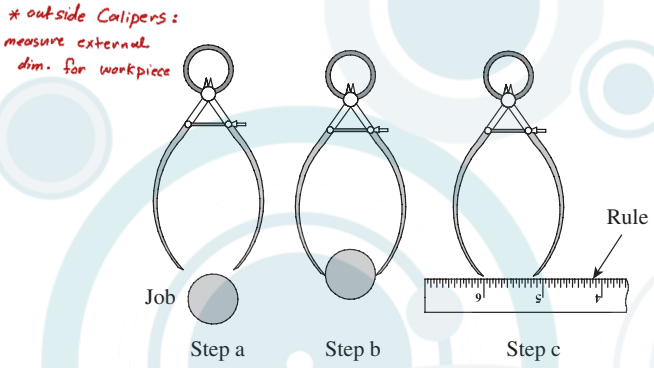


Fig. 4.19 Calliper being used to transfer a dimension from a job to a rule

within their range. Thus, callipers do only the job of transferring a dimension, but not of measuring instruments on their own. This is illustrated in Fig. 4.19, where a calliper is shown transferring the outer diameter of a job on to a graduated steel rule, to read the dimension accurately and conveniently. The outer diameter of a job is to be measured (Step a). Aligning the ends of the two legs of the calliper to a feature of the part being measured, like the one shown in Fig. 4.19, is accomplished quite easily (Step b) because the calliper provides for easy flexing of the two legs and a means of locking them into position whenever required. Now, simply laying the ends of the calliper on a steel rule facilitates easy measurement of the dimension in question (Step c). Thus, as the definition stated earlier mentions, physical duplication of the separation of reference and measured points is accomplished with a high degree of accuracy.

Callipers are available in various types and sizes. The two major types are the *firm joint calliper* and the *spring calliper*. A firm joint calliper, as the name itself suggests, can hold the position of two legs opened out to a particular degree unless moved by a certain force. This is possible because of higher friction developed at the joint between the two legs of the calliper. They are adjusted closely for size by gentle tapping of a leg. A locknut is needed to lock the calliper in a particular position. On the other hand, a spring calliper can hold a particular position due to the spring pressure acting against an adjusting nut. This permits a very careful control, and no lock is needed. Figure 4.20 illustrates the classification of callipers. Callipers are manufactured in a large number of sizes. They are designated not by their measurement ranges, but by the length of their legs,which range from 50 to 500 mm.

Figure 4.21 illustrates the different types of callipers. These are all simple callipers, whose ends are adjustable to transfer a measurement from the job to a steel rule. Although a member of the calliper family, a divider classified under callipers is simply referred to as a divider.

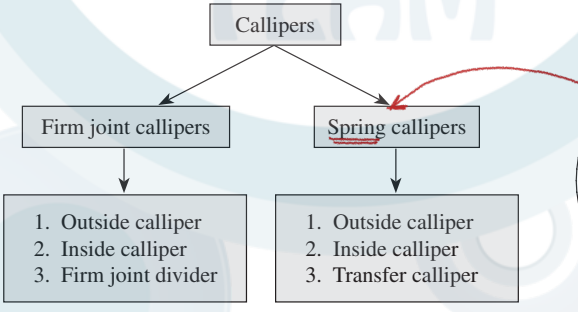


Fig. 4.20 Classification of callipers

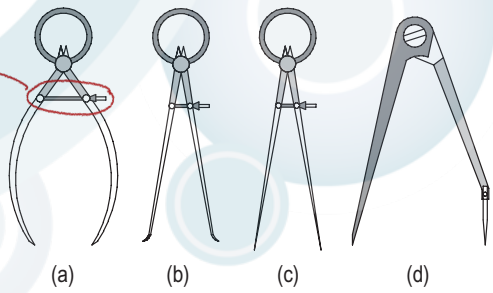


Fig. 4.21 Types of callipers (a) Outside calliper (b) Inside calliper (c) Divider (d) Hermaphrodite calliper

Outside calliper As the name suggests, an outside calliper is used to measure the outside or external dimensions. While taking measurements, the legs of the calliper should be set gently against the job either by a small physical force in case of a firm joint calliper or by an adjustment of the nut in case of a spring calliper. The user should ensure that a firm contact is established between the calliper and the job before transferring the measurement to a rule. One leg of the calliper is firmly held against a graduation on the steel rule to establish the reference point. The other leg is now gently transferred on to the rule to capture the measured point. The legs of callipers are made of alloy steel, with the measuring points being heat treated to withstand wear and tear. The legs are of a rectangular cross section, and should be free from cracks and any other type of flaw for longevity. The springs in spring callipers are made of spring steel, which is hardened and tempered. The spring force is adjusted by a knurled nut operating on a precision machined screw.

Inside calliper As illustrated in Fig. 4.21, the measuring ends of the legs of an inside calliper are shaped in the form of a hook. While taking measurements, the calliper legs are initially in a folded condition, which are inserted into the component. Now, the legs are stretched out to butt against the surface of the job. The calliper is carefully rocked over the centre. The feel provided as they pass the centre is the limit of their sensitivity.

Divider As with callipers, the primary use of dividers is to transfer measurements. However, they are used with line references rather than with surface references. Dividers are used for the following tasks: (a) transferring a dimension of a job to a rule for measurement, (b) transferring a dimension from one part to another part, and (c) transferring a dimension from a rule to a job for layout of the part. Scribing arcs during layout work is another chief use of dividers.

Hermaphrodite calliper It is essentially a scribing tool comprising one divider leg and one calliper leg. The scriber can be mounted by means of a locknut, as shown in Fig. 4.21. The chief advantage of a hermaphrodite calliper is that a scriber of any required shape and size can be fitted to it and used.

The proper use of the inside and outside callipers depends to a large extent on the skill of the person taking measurements. Measuring with a calliper consists of adjusting the opening so that its reference points duplicate the features of the job being measured. In other words, there is no other provision in a calliper that helps in its alignment than the reference points. As illustrated in Fig. 4.22, the greatest accuracy is achieved in case of callipers when the line of measurement coincides with a plane perpendicular to the job. The divider provides the best accuracy when the measurements are taken from well-marked lines, as shown in Fig. 4.22. Many a time measurements need to be taken between edges, in which case care must be exercised in ascertaining the proper way of taking measurements.

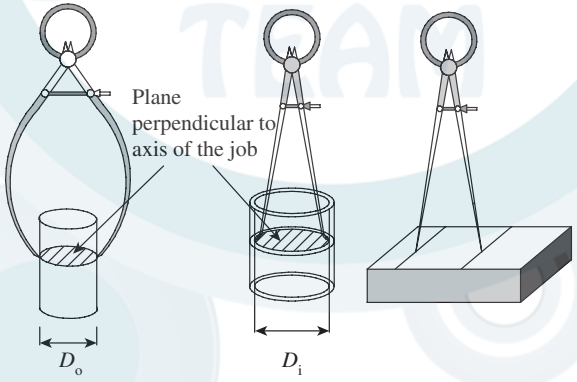


Fig. 4.22 Measurement using callipers (a) Outside calliper (b) Inside calliper (c) Divider

4.7 VERNIER INSTRUMENTS

The instruments discussed in this chapter until now can be branded 'non-precision' instruments, not for their lack of precision but for their lack of amplification. A steel rule can measure accurately up to 1 mm or at best up to 0.5 mm. It is not sensitive to variations in dimensions at much finer levels because of the inherent limitation in its design. On the other hand, vernier instruments based on the vernier scale principle can measure up to a much finer degree of accuracy. In other words, they can amplify finer variations in dimensions and can be branded as 'precision' instruments.

The vernier scale was invented in its modern form in 1631 by the French mathematician Pierre Vernier (1580–1637). Vernier instruments are being used for more than two centuries. The American, Joseph Brown, is credited with the invention of the vernier calliper. As is perhaps known to a student, a vernier scale provides a least count of up to 0.01 mm or less, which remarkably improves the measurement accuracy of an instrument. It has become quite common in the modern industry to specify dimensional accuracy up to 1 µm or less. It is the responsibility of an engineer to design and develop measuring instruments that can accurately measure up to such levels.

It will not be out of place here to briefly brush up our memory of the basic principles of a vernier scale. A vernier scale comprises two scales: the main scale and the vernier scale. Consider the scale shown in Fig. 4.23. Let us say that the main scale has graduations in millimetres up to a minimum division of 1 mm. The vernier scale also has graduations, having 10 equal divisions. In this example, 10 vernier scale divisions (VSDs) equal nine main scale divisions (MSDs). Obviously, the value of one VSD is less than one MSD. Such a vernier scale is called a *forward vernier*. On the other hand, suppose 10 VSDs equal 11 MSDs, the value of one VSD is more than that of one MSD. Such a vernier scale is called the *backward vernier*.

Calculation of least count The minimum length or thickness that can be measured with a vernier scale is called the *least count*. For a forward vernier shown in Fig. 4.23,

N VSD = (N–1) MSD

1 VSD = (N–1)/N MSD

Least count = 1 MSD – 1 VSD

Therefore, Least count = 1 MSD – (N – 1)/N MSD

Least count = [1– (N – 1)/N] MSD

Least count = 1 MSD/N

Total reading = MSR + (VC × LC), where MSR is the main scale reading, LC is the least count, and VC is the vernier coinciding division. Refer to Fig. 4.24 where the fourth division of the vernier coincides with a division on the main scale.

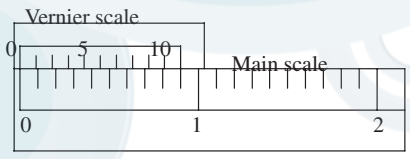


Fig. 4.23 Principle of a vernier scale

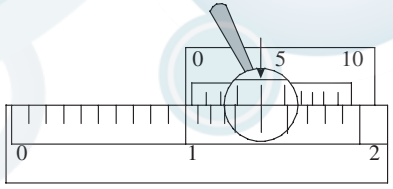


Fig. 4.24 Fourth division of vernier coinciding with a division on the main scale

Least count = 1 MSD/N = 1 mm/10 = 0.1 mm

Therefore, total reading = 1 + (4 × 0.1) = 1.4 mm

Digital read-out instruments and dial callipers are rapidly replacing vernier instruments. However, the principle of vernier measurement is basic to metrology, and the use of vernier instruments comprising vernier calliper, vernier depth gauge, vernier height gauge, vernier micrometers, etc., is still widespread in the industry. One can argue that anyone who can measure reliably with the vernier instruments can use the digital versions with equal reliability without any additional training. Even though the use of vernier instruments is not frequent for production inspection, they continue to play an important role in tool room and laboratory work. Production inspectors prefer limit gauges and comparators, which can speed up the inspection process considerably.

4.7.1 Vernier Calliper

A vernier calliper consists of two main parts: the main scale engraved on a solid L-shaped frame and the vernier scale that can slide along the main scale. The sliding nature of the vernier has given it another name—*sliding calliper*. The main scale is graduated in millimetres, up to a least count of 1 mm. The vernier also has engraved graduations, which is either a forward vernier or a backward vernier. The vernier calliper is made of either stainless steel or tool steel, depending on the nature and severity of application.

Figure 4.25 illustrates the main parts of a vernier calliper. The L-shaped main frame also serves as the fixed jaw at its end. The movable jaw, which also has a vernier scale plate, can slide over the entire length of the main scale, which is engraved on the main frame or the beam. A clamping screw enables clamping of the movable jaw in a particular position after the jaws have been set accurately over the job being measured. This arrests further motion of the movable jaw, so that the operator can note down the reading in a convenient position. In order to capture a dimension, the operator has to open out the two jaws, hold the instrument over the job, and slide the movable jaw inwards, until the two jaws are in firm contact with the job. A fine adjustment screw enables the operator to accurately enclose the portion of the job where measurement is required by applying optimum clamping pressure. In the absence of the fine adjustment screw, the operator has to rely on his careful judgement to apply the minimum force that is required to close the two jaws firmly over the job. This is easier said than done, since any excessive application of pressure increases wear and tear of the instrument and may also cause damage to delicate or fragile jobs. The two jaws are shaped in such a manner that

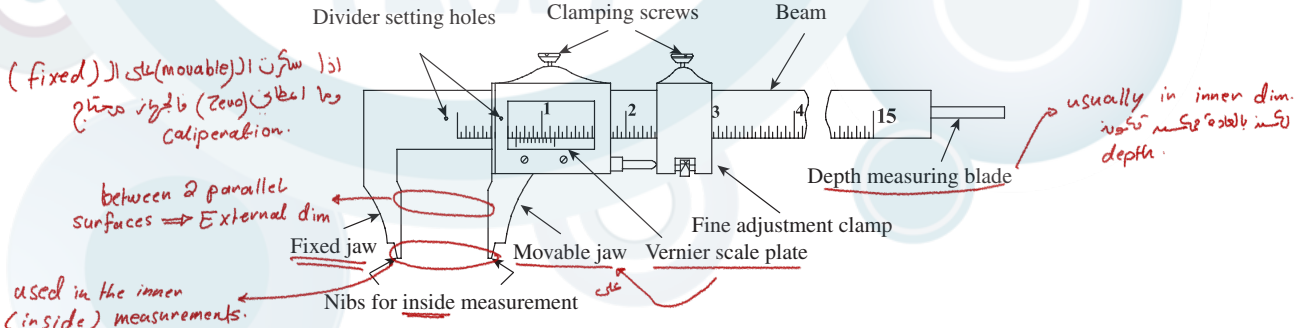


Fig. 4.25 Main parts of a vernier calliper

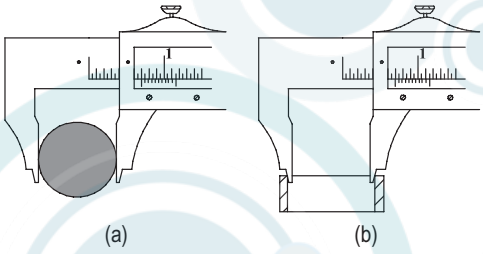


Fig. 4.26 Measurement of dimensions (a) Outside dimension (b) Inside dimension

they can be used to measure both inside and outside dimensions. Notice the nibs in Fig. 4.25, which can be used to measure inside dimension. Figure 4.26 illustrates the method of measuring inside and outside dimensions using a vernier calliper. Whenever the vernier slides over the main frame, a depth-measuring blade also slides in and out of the beam of the calliper. This is a useful attachment for measuring depths to a high degree of accuracy. Divider setting holes are provided, which enable the use of a divider to aid the measurement process.

Measuring a diameter is easier than measuring between flat surfaces, because the diameter is the greatest distance separating the reference and the measured points. Compared to the measurement between flat surfaces, the area of contact between the calliper and the job is much lesser in diameter measurement. Therefore, the resultant force acting either on the job or on the jaws of the calliper is lesser, with the result that there is no deformation or buckling of the jaws. This not only improves the accuracy of measurement, but also reduces the wear and tear of the instrument. Whether the measurement is done for the inside diameter or outside diameter, the operator has to rely on his/her feel to judge if proper contact is made between the measured surfaces and also that excessive force is not exerted on the instrument or the job. Continued closing of the calliper will increase the springing. High gauging pressure causes rapid wear of the jaws, burnishes the part (localized hardening of metal), and may cause damage to the calliper. The following guidelines are useful for the proper use of a vernier calliper:

1. Clean the vernier calliper and the job being measured thoroughly. Ensure that there are no burrs attached to the job, which could have resulted from a previous machining operation.
2. When a calliper's jaws are fully closed, it should indicate zero. If it does not, it must be recalibrated or repaired.
3. Loosen the clamping screw and slide the movable jaw until the opening between the jaws is slightly more than the feature to be measured.
4. Place the fixed jaw in contact with the reference point of the feature being measured and align the beam of the calliper approximately with the line of measurement.
5. Slide the movable jaw closer to the feature and operate the fine adjustment screw to establish a light contact between the jaws and the job.
6. Tighten the clamp screw on the movable jaw without disturbing the light contact between the calliper and the job.
7. Remove the calliper and note down the reading in a comfortable position, holding the graduations on the scale perpendicular to the line of sight.
8. Repeat the measurement a couple of times to ensure an accurate measurement.
9. After completing the reading, loosen the clamping screw, open out the jaws, and clean and lubricate them.
10. Always store the calliper in the instrument box provided by the supplier. Avoid keeping the vernier calliper in the open for long durations, since it may get damaged by other objects or contaminants.
11. Strictly adhere to the schedule of periodic calibration of the vernier calliper.

According to IS: 3651-1974,vernier callipers are of three types: type A, type B, and type C. While all the three types have the scale on the front of the beam, type A vernier scale has jaws on both sides for external and internal measurements, along with a blade for depth measurement. Type B, shown in Fig. 4.25, is provided with jaws on one side only for both external and internal measurements. Type C has jaws on both sides for making the measurements. However, the jaws have knife edge faces for marking purpose. The recommended measuring ranges for vernier callipers are 0–125, 0–200, 0–250, 0–300, 0–500, 0–750, 0–1000, 750–1500, and 750–2000 mm.

Dial Calliper

A vernier calliper is useful for accurate linear measurements. However, it demands basic mathematical skill on the part of the user. One should be able to do simple calculations involving MSD, vernier coinciding division, and least count, in order to compute the measured value of a dimension. In addition, considerable care should be exercised in identifying the coinciding vernier division. These problems can be offset by using a dial calliper (Fig. 4.27).

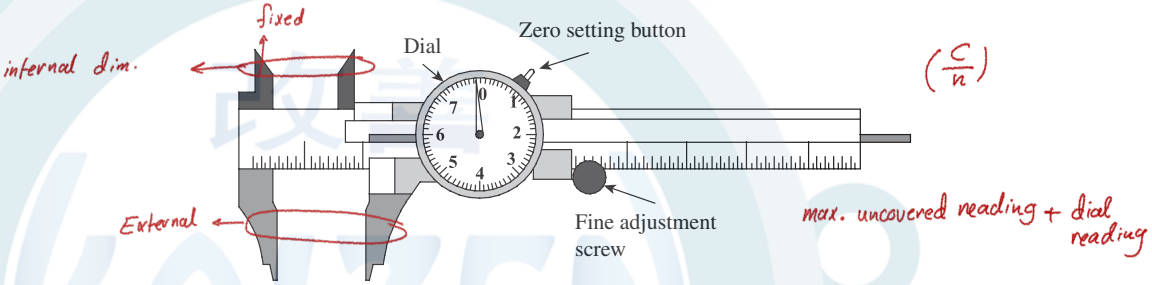


Fig. 4.27 Dial calliper

In a dial calliper, the reading can be directly taken from a dial gauge that is attached to the calliper. The dial gauge has its own least count, which is clearly indicated on the face of the dial. By multiplying the value of the reading indicated by the least count, one can calculate the measured value easily. A small but precise pair of rack and pinion drives a pointer on a circular scale. This facilitates direct reading without the need to read a vernier scale. Typically, the pointer undergoes one complete rotation per centimetre or per millimetre of linear measurement. This measurement should be added to the main scale reading to get the actual reading. A dial calliper also eliminates parallax error, which is associated with a conventional vernier calliper.

A dial calliper is more expensive than the vernier calliper. In addition, the accuracy of the reading mechanism of the dial calliper is a function of length of travel, unlike the vernier calliper that has the same accuracy throughout its length. A dial calliper is also subject to malfunctioning because of the delicate nature of the dial mechanism.

Electronic Digital Calliper

An electronic digital calliper is a battery-operated instrument that displays the reading on a liquid crystal display (LCD) screen. The digital display eliminates the need for calculations and provides an easier way of taking readings. Figure 4.28 illustrates the main parts of an electronic digital calliper.

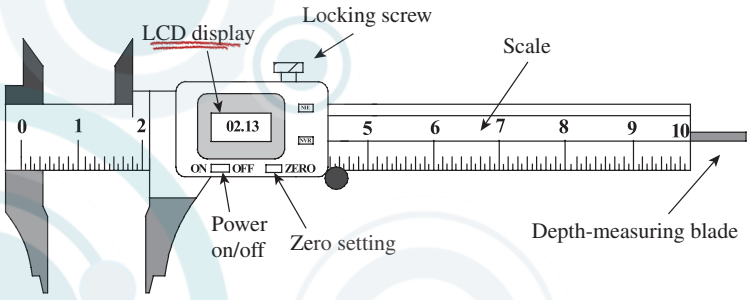


Fig. 4.28 Electronic digital calliper

The LCD display is turned on or off with a button. In order to initialize the instrument, the external jaws are brought together until they touch and the 'zero button' is pressed to set the reading to zero. The digital calliper can now be used to measure a linear dimension. Some digital callipers can be switched between centimetres or millimetres, and inches. Digital callipers are made of stainless steel and are generally available in three sizes: 150, 200, and 300 mm.

The two greatest advantages of an electronic digital calliper are its electronic calculator functions and capability to be interfaced with a computer. It can be set to either metric or British system of units. The 'floating zero' option allows any place within the scale range to be set to zero. The digital display will then exhibit either plus or minus deviations of the jaw from a reference value. This enables the instrument to be also used as a limit gauge. More importantly, a digital calliper can be interfaced with a dedicated recorder or personal computer through a serial data cable. The digital interface provides secured storage for a series of readings, thereby improving the reliability of the records. It can be connected to a printer to provide a printed record or can be directly interfaced with a computer of a statistical control system.

4.7.2 Vernier Depth Gauge

Section 4.7.1 already highlighted the construction and working principle of a depth gauge. However, even though it is simple to operate, it cannot take measurements finer than 1 mm accuracy. A vernier depth gauge is a more versatile instrument, which can measure up to 0.01 mm or even finer accuracy. Figure 4.29 illustrates the constructional features of a vernier depth gauge. The lower surface of the base has to butt firmly against the upper surface of the hole or recess whose depth is to be measured. The vernier scale is stationary and screwed onto the slide, whereas the main scale can slide up and down. The nut on the slide has to be loosened to move the main scale. The main scale is lowered into the hole or recess, which is being measured. One should avoid exerting force while pushing the scale against the surface of the job being measured, because this will not only result in the deformation of the scale resulting in erroneous measurements, but also accelerate the wear and tear of the instrument. This problem is eliminated thanks to the fine adjustment clamp provided with the instrument. A fine adjustment wheel will rotate the fine adjustment screw, which in turn will cause finer movement of the slide. This ensures firm but delicate contact with the surface of the job.

Vernier depth gauges can have an accuracy of up to 0.01 mm. Periodic cleaning and lubrication are mandatory, as the main scale and fine adjustment mechanism are always in motion in the process of taking measurements.

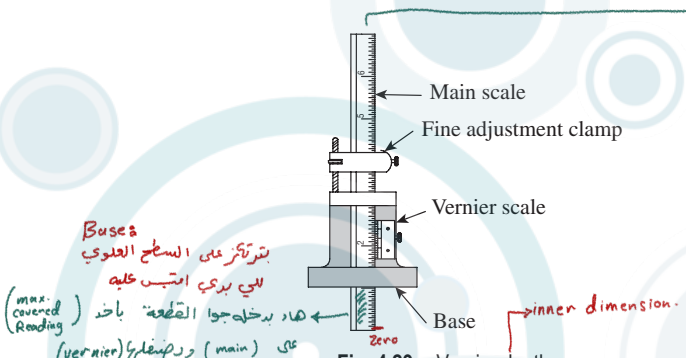


Fig. 4.29 Vernier depth gauge

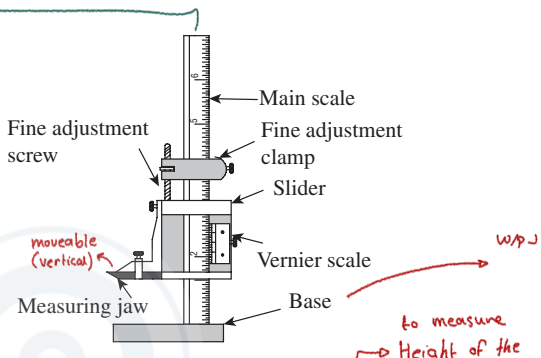


Fig. 4.30 Vernier height gauge

4.7.3 Vernier Height Gauge

In a vernier height gauge, as illustrated in Fig. 4.30, the graduated scale or bar is held in a vertical position by a finely ground and lapped base. A precision ground surface plate is mandatory while using a height gauge. The feature of the job to be measured is held between the base and the measuring jaw. The measuring jaw is mounted on a slider that moves up and down, but can be held in place by tightening of a nut. A fine adjustment clamp is provided to ensure very fine movement of the slide in order to make a delicate contact with the job. Unlike in depth gauge, the main scale in a height gauge is stationary while the slider moves up and down. The vernier scale mounted on the slider gives readings up to an accuracy of 0.01 mm.

Vernier height gauges are available in sizes ranging from 150 to 500 mm for precision tool room applications. Some models have quick adjustment screw release on the movable jaw, making it possible to directly move to any point within the approximate range, which can then be properly set using the fine adjustment mechanism. Vernier height gauges find applications in tool rooms and inspection departments. Modern variants of height gauges such as optical and electronic height gauges are also becoming increasingly popular.

4.8 MICROMETER INSTRUMENTS

The word 'micrometer' is known by two different meanings. The first is as a unit of measure, being one thousandth of a millimetre. The second meaning is a hand-held measuring instrument using a screw-based mechanism. The word *micrometer* is believed to have originated in Greece, the Greek meaning for this word being *small*. The first ever micrometer screw was invented by William Gascoigne of Yorkshire, England, in the 17th century and was used in telescopes to measure angular distances between stars. The commercial version of the micrometer was released by the Browne & Sharpe Company in the year 1867. Obviously, micrometer as an instrument has a long and cherished history in metrological applications. There have been many variants of the instrument, and modern industry makes use of highly sophisticated micrometers, such as digital micrometers and laser scan micrometers. A micrometer can provide better least counts and accuracy than a vernier calliper. Better accuracy results because of the fact that the line of measurement is in line with the axis of the instrument, unlike the vernier calliper that does not conform to this condition. This fact is best explained by *Abbe's principle*, which states that *'maximum accuracy may be obtained only when the standard is in line with the axis of the*

part being measured'. Figure 4.31 illustrates the relevance of Abbe's law for micrometers and vernier callipers.

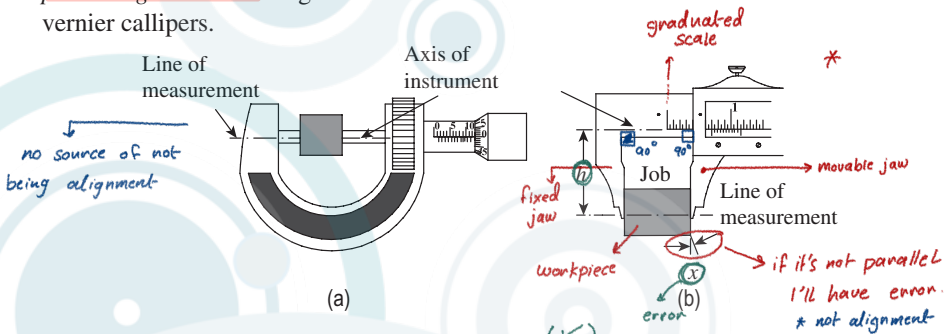


Fig. 4.31 Conformity to Abbe's law (a) Micrometer (b) Vernier calliper

In case of a micrometer, the axis of the job being measured is in line with the line of measurement of the instrument, as illustrated in Fig. 4.31(a). In case of a vernier calliper, for the reading to be accurate, the beam would have to be perfectly straight and the two jaws perfectly at 90° to it. However, this is rarely the case. There is always some lack of straightness of the beam, and the jaws may not be perfectly square with the beam. With continuous usage and wear and tear, the jaws will develop more and more play (Play refers to uncontrolled movements due to slip of one part over the other.) because of repeated sliding movements. Therefore, a certain amount of angular error, marked as x in Fig. 4.31(b), will always be present. This angular error also depends on how far the line of measurement is from the axis of the instrument. The higher the value of this separation h, the greater will be the angular error. We can therefore conclude that *the degree to which an instrument conforms to Abbe's law determines its inherent accuracy.*

4.8.1 Outside Micrometer

Figure 4.32 illustrates the details of an outside micrometer. It consists of a C-shaped frame with a stationary anvil and a movable spindle. The spindle movement is controlled by a precision ground screw. The spindle moves as it is rotated in a stationary spindle nut. A graduated scale is engraved on the stationary sleeve and the rotating thimble. The zeroth mark on the thimble will coincide with the zeroth division on the sleeve when the anvil and spindle faces are brought together. The movement of the screw conforms to the sets

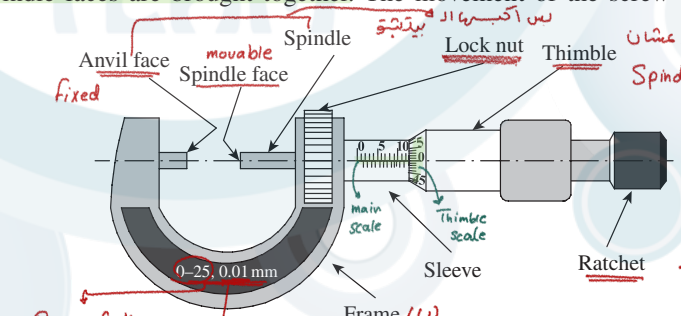


Fig. 4.32 Outside micrometer

How to read micrometers ?
main scale smallest dev. = 0.05
7.30 mm
on the Thimble = 0.01 mm
with 50 graduation
(½ mm per revolution)
0.5/50 = 0.01

of graduations. The locknut enables the locking of the spindle while taking a reading. The ratchet ensures a 'feel' while taking a reading and prevents application of excessive force on the job. The ranges of micrometers are normally 0–25, 25–50, or 0–50 mm. The maximum range of micrometers is limited to 500 mm.

A micrometer is made of steel or cast steel. The measuring faces are hardened to about 60–65 HRC since they are in constant touch with metallic jobs being measured. If warranted, the faces are also tipped with tungsten carbide or a similar material to prevent rapid wear. The anvil is ground and lapped to a high degree of accuracy. The material used for thimble and ratchet should be wear-resistant steel.

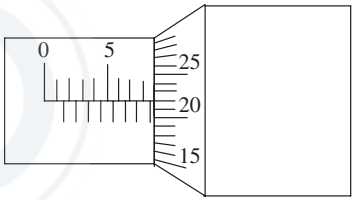


Fig. 4.33 Reading an outside micrometer

Micrometers with metric scales are prevalent in India. The graduations on the sleeve are in millimetres and can be referred to as the main scale. If the smallest division on this scale reads 0.5 mm, each revolution of the thimble advances the spindle face by 0.5 mm. The thimble, in turn, will have a number of divisions. Suppose the number of divisions on the thimble is 50, then the least count of the micrometer is 0.5/50, that is, 0.01 mm. Figure 4.33 illustrates how the micrometer scale is read when a job is held between the anvil face and the spindle face.

In this example, the main scale reading is 8.5 mm, which is the division immediately preceding the position of the thimble on the main scale. As already pointed out, let us assume the least count of the instrument to be 0.01 mm. The 22nd division on the thimble is coinciding with the reference line of the main scale. Therefore, the reading is as follows:

$$8.5 + 22\,(0.01)\,\text{mm} = 8.72\,\text{mm}$$

Thus, a micrometer is a simple instrument to use. However, there are two precautions to be observed while reading a micrometer. The thimble must be read in the correct direction. The other precaution concerns the zero position on the thimble. When passing the index line on the main scale, there is a chance to read an extra 0.5 mm. This is caused by the fact that the next main scale graduation has begun to show but has not yet fully appeared. This is avoided by being careful to read only full divisions on the barrel. Assuming that these simple precautions are adhered to, a micrometer has many advantages over other linear measurement instruments. It has better readability than a vernier scale and there is no parallax error. It is small, lightweight, and portable. It retains accuracy over a longer period than a vernier calliper and is less expensive. On the flip side, it has a shorter measuring range and can only be used for end measurement.

Types of Micrometers

A micrometer is a versatile measuring instrument and can be used for various applications by simply changing the anvil and the spindle face. For example, the anvil may be shaped in the form of a V-block or a large disk. Figure 4.34 shows a few variants, namely the disk micrometer, screw thread micrometer, dial micrometer, and blade micrometer. The following paragraphs briefly highlight the use of each type of micrometer in metrology applications:

Disk micrometer It is used for measuring the distance between two features with curvature. A tooth span micrometer is one such device that is used for measuring the span between the two teeth of a gear. Although it provides a convenient means for linear measurement, it is prone to error in measurement when the curvature of the feature does not closely match the curvature of the disk.

Screw thread micrometer It measures pitch diameters directly. The anvil has an internal '*vee*', which fits over the thread. Since the anvil is free to rotate, it can accommodate any rake range of thread. However, interchangeable anvils need to be used to cover a wide range of thread pitches. The spindle has a conical shape and is ground to a precise dimension.

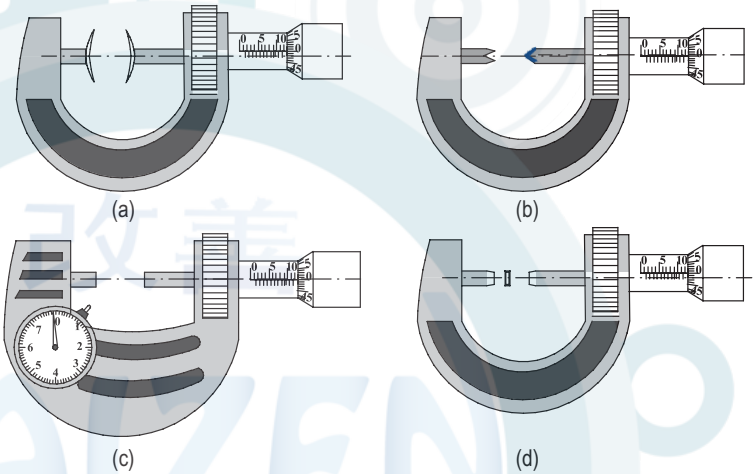


Fig. 4.34 Types of micrometers (a) Disk type (b) Screw thread type (c) Dial type (d) Blade type

Dial micrometer The dial indicator fixed to the frame indicates the linear displacement of a movable anvil with a high degree of precision. It is especially useful as a comparator for GO/NO-GO judgement in mass production. The dial micrometer normally has an accuracy of 1 µm and repeatability of 0.5 µm. Instruments are available up to 50 mm measuring distance, with a maximum measuring force of 10 N. The dial tip is provided with a carbide face for a longer life.

Blade micrometer The anvil and spindle faces are in the form of narrow blades and useful for measuring narrow grooves, slots, keyways, and recesses. The blade thickness is around 0.75–1 mm. The spindle does not rotate when the movable blade is moving along the measuring axis. Due to the slender nature of the instrument and non-turning spindle working against a rotating screw, it is vulnerable to rapid wear and tear and needs careful use and maintenance.

Universal micrometer It has interchangeable anvils such as flat, spherical, spline, disk, or knife edge. It is called universal because of its modular design. The micrometer fitted with the required accessories can function as an outside micrometer, a depth micrometer, a step micrometer, etc.

4.8.2 Vernier Micrometer

A micrometer that we considered hitherto can provide an accuracy of at best 0.01 mm or 10 µm. Placing a vernier scale on the micrometer permits us to take readings up to the next decimal place. In other words, one can accurately measure up to 1 µm or 0.001 mm, which is an excellent proposition for any precision workmanship. As illustrated in Fig. 4.35, in addition to the barrel and thimble scales, a vernier scale is provided next to the barrel scale. Divisions on this vernier scale have to be read in conjunction with the barrel scale to provide the next level of discrimination in readings. The vernier scale consists of a number of equally spaced lines, which are numbered from 0 to 5 or 10, depending on the scale.

The principle of measurement of a vernier micrometer is very similar to that of a vernier calliper. If a division on the thimble is exactly coinciding with the reference line (line marked 0 in the vernier scale in Fig. 4.35) of the vernier scale, the reading is taken in a way similar to an ordinary micrometer explained earlier. However, if none of the divisions on the thimble coincide with the reference line, we need to examine which division on the thimble coincides with one of the divisions on the vernier scale. Hence, an additional step is involved in the calculation since the vernier reading should be taken into account.

Refer to Fig. 4.36, which shows a sample reading. In this case, the thimble has crossed the 12.5 mm mark on the barrel scale. None of the divisions on the thimble coincides with the zeroth line on the vernier scale, that is, the reference line on the barrel. However, the reference line is between the 24th and 25th divisions on the thimble. Suppose the thimble has 50 divisions, and five divisions on the vernier scale correspond to six divisions on the thimble, we can calculate the least count of the instrument as follows.

If one complete rotation of the thimble moves it by 0.5 mm on the barrel scale, the least count of the micrometer scale is 0.5/50 = 0.01 mm.

Since five divisions on the vernier scale correspond to six divisions on the thimble, the least count of the vernier scale is equal to 0.01/5 = 0.002 mm. In Fig. 4.36, the fourth division on the vernier scale is coinciding with a division on the thimble.

Therefore, the reading is 12.5 + 24 (0.01) + 4 (0.002) = 12.748 mm.

Guidelines for Use of Micrometers

1. Before placing the micrometer on the job being measured, bring it near the desired opening. Do this by rolling the thimble along the hand but not by twirling. Hold the micrometer

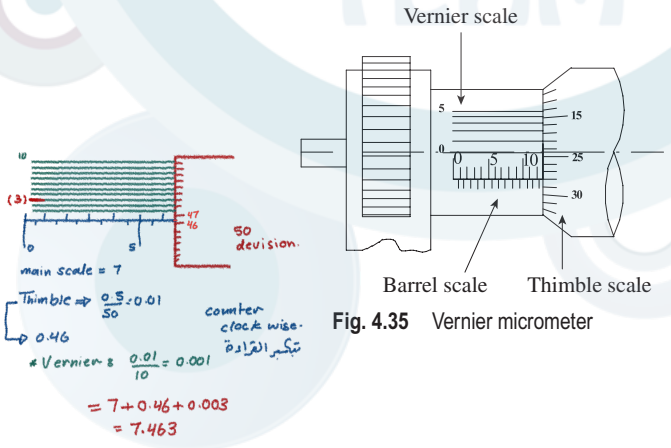


Fig. 4.35 Vernier micrometer

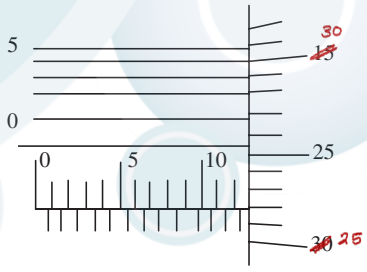


Fig. 4.36 Reading a vernier scale

firmly with one hand, and use the feel of the hand to ensure that the axis of the micrometer is perpendicular to the reference plane of the job. Close the micrometer using the ratchet stop until it disengages with a click.

2. Even though a micrometer can be locked in position by tightening the clamp ring (locknut) and used as a snap gauge for inspection purposes, it is not basically designed for this role. Locking the spindle movement and forcing the measuring faces over the job result in sliding friction, which accelerates wear on the contact surfaces as well as on the micrometer screw.
3. The locknut is a memory device. It retains the reading so that it can be read in a convenient position. However, avoid tightening the locknut when the spindle is withdrawn. Doing so will injure the clamping mechanism.
4. It is not wise to buy a micrometer that does not have a controlled force feature. Excessive force while closing the measuring faces over the job will result in rapid wear and tear of the instrument. A ratchet stop acts as an overriding clutch that holds the gauging force at the same amount for each measurement regardless of the differences in manual application of force.
5. While measuring the diameter of a cylindrical part, rock the cylinder to find the maximum opening that provides the desired feel.
6. Do not expect the micrometer to guarantee reliable measurement if it is (a) dirty; (b) poorly lubricated; (c) poorly adjusted; or (d) closed too rapidly.
7. At the end of each day, the micrometer should be wiped clean, visually inspected, oiled, and replaced in its case to await the next use.

4.8.3 Digital Micrometer

The 'multifunction' digital micrometer is becoming very popular in recent times. The readings may be processed with ease. The push of a button can convert a reading from decimal to inch and vice versa. Any position of the spindle can be set to zero and the instrument can be used to inspect a job within a specified tolerance. The instrument can be connected to a computer or a printer. Most instruments can record a series of data and calculate statistical information such as mean, standard deviation, and range (Fig. 4.37).

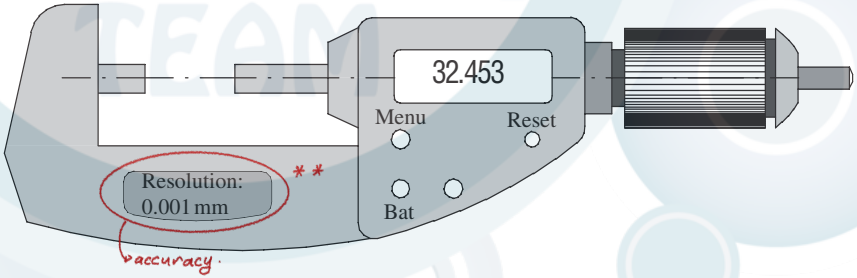


Fig. 4.37 Digital micrometer

The instrument is recommended to be used along with a stand for ease of measurement. The spindle is made of stainless steel and measuring faces are carbide tipped for a longer life. A locking clamp ensures locking of spindle at any desired setting. A constant and low measuring force is ensured by the thimble mechanism. Most of the instruments have a least count of

0.001 mm. An LCD screen displays the reading with absolute linear scale with simple digimatic data collection for personal computer (SPC) data output. An easy push button control is provided to choose the various functions of the instrument. The push buttons controlling the various functions are as follows:

1. ON/OFF: To power the instrument on or off
2. IN/MM: To select either inch or metric system of measurement
3. ZERO: To set the screen display to zero at any desired position
4. HOLD: To hold the measurement taken until the push button is operated again
5. ORIGIN: To set the minimum value for the micrometer depending upon its size; micrometer count commences from this value
6. Alarm indicator: To indicate low voltage and counting value composition error

4.8.4 Inside Micrometer Calliper

The inside micrometer calliper is useful for making small measurements from 5 to 25 mm. In this instrument, unlike a regular micrometer, the axis of the instrument does not coincide with the line of measurement. In addition, unlike the outside micrometer where there is a surface contact between the job and the instrument, the contact between the job and the instrument is line contact. The *nibs*, as the contacts are called, are ground to a small radius. As a necessity, this radius has to be smaller than the smallest radius the instrument can measure. Therefore, all measurements are made with line contacts.

As illustrated in Fig. 4.38, the movable jaw can be moved in and out by the rotation of the thimble. One complete rotation of the thimble moves it by one division on the barrel scale. A locknut can be operated to hold the position of the movable jaw for ease of noting down a reading. While taking measurements, it needs to be rocked and centralized to assure that the axis of the instrument is parallel to the line of measurement. This makes the instrument prone to rapid wear. It is therefore needless to say that the instrument needs to be checked and calibrated regularly.

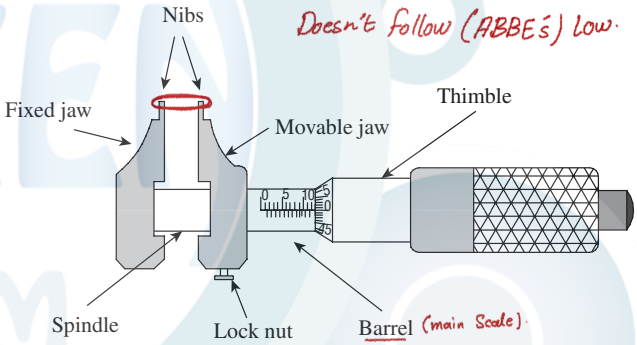


Fig. 4.38 Inside micrometer calliper

4.8.5 Inside Micrometer

This instrument perfectly complies with Abbe's law. The axis of an inside micrometer is also its line of measurement. It is useful for measuring the inside diameter of cylinders, rings, and other machine parts. The inside micrometer set has several accessories, which have to be assembled together for taking the readings. The main unit is the measuring head, which has a thimble that moves over a barrel, same as in the case of an outside micrometer. Graduated scales are provided on the barrel and thimble, which give readings up to an accuracy of 0.01 mm, but with a limited range. The rear end of the measuring head has a contact surface, whereas extension

rods of various lengths can be fitted to the front end of the measuring head. A set of extension rods are provided with the instrument to cover a wide range of measurements. The rod ends are spherical and present nearly point contact to the job being measured. A chuck attached to the spindle facilitates the attachment of extension rods. Using a particular extension rod, the distance between contact surfaces can be varied by rotating the thimble up to the range of the micrometer screw. Higher diameters and distances can be measured using longer extension rods. Figure 4.39 illustrates the construction details of an inside micrometer.

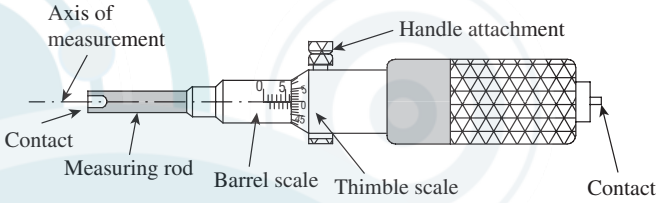


Fig. 4.39 Inside micrometer

The inside micrometer is more common than the inside micrometer calliper because of the flexibility it affords to measure a large range of dimensions. A range of 25 mm above the length of extension rods is commonly used in shops. A standard set will have five extension rods of ranges 50–75, 75–100, 100–125, 125–150, 150–175, and 175–200 mm. In addition to extension rods, a spacing collar (usually 12.5 mm in length) is provided for smaller adjustments in the range of measurements. The micrometer is also provided with a detachable handle for easier handling of the instrument.

The best practice for using an inside micrometer is to first measure the dimension approximately by using a steel rule. Then select a suitable extension rod that can adequately cover the range of measurements. Insert the extension rod into the chuck and set the instrument to read zero. Now fix the handle and lower the instrument into the gap where the dimension is to be measured. Operate the thimble until the two contact surfaces establish a firm contact with the surfaces of the job. While measuring diameters, it is always recommended to lightly move the instrument to and fro so that the actual diameter is sensed by the person taking measurements. Now, operate the locknut and take out the instrument. The micrometer reading has to be added to the length of the extension rod to get the actual reading.

4.8.6 Depth Micrometer

An alternative to vernier depth gauge is the depth micrometer. In fact, most shop floor engineers vouch for its superiority over vernier depth gauges because of its greater measuring range, better reliability, and easier usability. One peculiarity of this instrument is that it reads in reverse from other micrometers. Looking from the ratchet side, a clockwise rotation moves the spindle downwards, that is, into the depth of the job being measured. Therefore, the entire barrel scale is visible when the tip of the measuring rod is in line with the bottom surface of the base. As the measuring rod advances into the depths, the thimble will move over the barrel scale. Reliable measurements of up to 0.01 mm are possible with this instrument. Figure 4.40 illustrates the parts of a depth micrometer. The bottom flat surface of the base butts over the reference plane on the job, and the micrometer scale directly gives the depth of the measuring rod tip from the reference plane.

The head movement of the depth micrometer is usually 25 mm. Inter-changeable measuring rods, similar to an inside micrometer discussed in the previous section, provide the required measuring range for the instrument. Measuring rods of up to 250 mm length are used in a standard set.

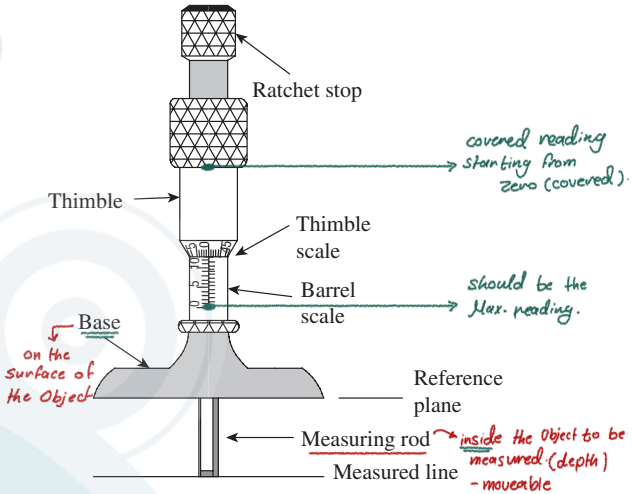


Fig. 4.40 Depth micrometer

4.8.7 Floating Carriage Micrometer

A floating carriage micrometer, sometimes referred to as an effective diameter-measuring micrometer, is an instrument that is used for accurate measurement of 'thread plug gauges'. Gauge dimensions such as outside diameter, pitch diameter, and root diameter are measured with the help of this instrument. All these dimensions have a vital role in thread plug gauges, since the accuracy and interchangeability of the component depend on the gauges used. To reduce the effect of slight errors in the micrometer screws and measuring faces, this micrometer is basically used as a comparator. Figure 4.41 illustrates a floating carriage micrometer.

The carriage has a micrometer with a fixed spindle on one side and a movable spindle with the micrometer on the other side. The carriage moves on a finely ground 'V' guide way or an antifriction guide way to facilitate movement in a direction parallel to the axis of the plug gauge mounted between the centres. The micrometer has a non-rotary spindle with a least count of up to 0.001 or 0.002 mm. The instrument is very useful for thread plug gauge manufacturers, in gauge calibration laboratories (established under NABL accreditation), and in standard rooms where in-house gauge calibration is carried out.

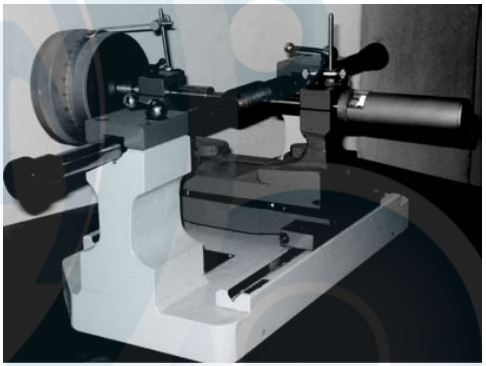


Fig. 4.41 Floating carriage micrometer

4.9 SLIP GAUGES

Hitherto we have seen instruments such as vernier calliper, depth gauge, and micrometer, which can facilitate measurement to a fairly high degree of accuracy and precision. All these measurements involve line standards. The accuracy of these instruments depends on the accuracy of the workmanship involved in their manufacture. Any minor misalignment or error in a screw can lead to errors in measurement. Repetitive use of a screw or joint results in rapid

wear and tear, which can lead to accumulation of errors in measurement within a short time. Slip gauges, also called gauge blocks, can counter some of these limitations and provide a high degree of accuracy as *end standards*. In fact, slip gauges are a direct link between the measurer and the international length standards.

The origin of gauge blocks can be traced to the 18th century Sweden, where 'gauge sticks' were known to have been used in machine shops. However, the modern-day slip gauges or gauge blocks owe their existence to the pioneering work done by C.E. Johansson, a Swedish armoury inspector. Therefore, gauge blocks are also known as *Johansson gauges*. He devised a set of slip gauges manufactured to specific heights with a very high degree of accuracy and surface finish. He also proposed the method of 'wringing' slip gauges to the required height to facilitate measurements. He also emphasized that the resulting slip gauges, to be of universal value, must be calibrated to the international standard. Johansson was granted a patent for his invention in the year 1901 and formed the Swedish company CE Johansson AB in the year 1917. He started manufacturing and marketing his gauge blocks to the industry, and found major success in distant America. One of his customers was Henry Ford with whom he signed a cooperative agreement to establish a gauge making shop at his Cadillac automobile company. The development of 'GO' and 'NO-GO' gauges also took place during this time.

Figure 4.42 illustrates the functional features of a slip gauge. It is made of hardened alloy steel having a 30 mm × 10 mm cross section. Steel is the preferred material since it is economical and has the same coefficient of thermal expansion as a majority of steel components used in production. Hardening is required to make the slip gauge resistant to wear. Hardening is followed by stabilizing at a sub-zero temperature to relieve stresses developed during heat treatment. This is followed by finishing the measuring faces to a high degree of accuracy, flatness, and surface finish. The height of a slip gauge is engraved on one of the rectangular faces, which also features a symbol to indicate the two measured planes. The length between the measuring surfaces, flatness, and surface conditions of measuring faces are the most important requirements of slip gauges.

Carbide gauge blocks are used for their superior wear resistance and longer life. They also have low coefficient of thermal expansion. However, they are quite expensive and used when rapid wear of gauges is to be avoided.

Several slip gauges are combined together temporarily to provide the end standard of a specific length. A set of slip gauges should enable the user to stack them together to provide an accuracy of up to one-thousandth of a millimetre or better. In order to achieve this, individual gauges must be available in dimensions needed to achieve any combination within the available number of gauges. The surfaces of neighbouring slip gauges should stick so close together that there should not be any scope for even a layer of air to be trapped between them, which can add error to the final reading. For this to happen, there should be absolute control over the form, flatness, parallelism, surface finish, dimensional stability of material, and homogeneity of gauging surfaces. While building slip gauges to the required height, the surfaces of slip gauges are pressed

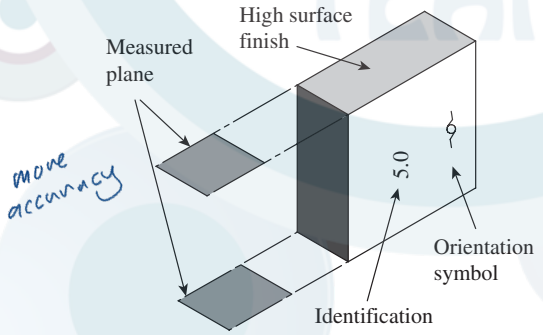


Fig. 4.42 Functional features of a slip gauge

into contact by imparting a small twisting motion while maintaining the contact pressure. The slip gauges are held together due to molecular adhesion between a liquid film and the mating surfaces. This phenomenon is known as 'wringing'.

4.9.1 Gauge Block Shapes, Grades, and Sizes

Slip gauges are available in three basic shapes: rectangular, square with a central hole, and square without a central hole. Rectangular blocks are the most commonly used since they can be used conveniently where space is restricted and excess weight is to be avoided. Square slip gauges have larger surface area and lesser wear rate because of uniform distribution of stresses during measurements. They also adhere better to each other when wrung together. Square gauge blocks with central holes permit the use of tie rods, which ensure that the built-up slip gauges do not fall apart.

Slip gauges are classified into grades depending on their *guaranteed* accuracy. The grade defines the type of application for which a slip gauge is suited, such as inspection, reference, or calibration. Accordingly, slip gauges are designated into five grades, namely grade 2, grade 1, grade 0, grade 00, and inspection grade.

Grade 2 This is the workshop-grade slip gauge. Typical uses include setting up machine tools, milling cutters, etc., on the shop floor.

Grade 1 This grade is used for tool room applications for setting up sine bars, dial indicators, calibration of vernier, micrometer instruments, and so on.

Grade 0 This is an inspection-grade slip gauge. Limited people will have access to this slip gauge and extreme care is taken to guard it against rough usage.

Grade 00 This set is kept in the standards room and is used for inspection/calibration of high precision only. It is also used to check the accuracy of the workshop and grade 1 slip gauges.

Calibration grade This is a special grade, with the actual sizes of slip gauges stated on a special chart supplied with the set of slip gauges. This chart gives the exact dimension of the slip gauge, unlike the previous grades, which are presumed to have been manufactured to a set tolerance. They are the best-grade slip gauges because even though slip gauges are manufactured using precision manufacturing methods, it is difficult to achieve 100% dimensional accuracy. Calibration-grade slip gauges are not necessarily available in a set of preferred sizes, but their sizes are explicitly specified up to the third or fourth decimal place of a millimetre.

Many other grading standards are followed for slip gauges, such as JIS B 7506-1997 (Japan), DIN 861-1980 (Germany), ASME (USA), and BS 4311:Part 1:1993 (UK). Most of these standards assign grades such as A, AA, AAA, and B. While a grade B may conform to the workshop-grade slip gauge, grades AA and AAA are calibration and reference grades, respectively.

Slip gauges are available in standard sets in both metric and inch units. In metric units, sets of 31, 48, 56, and 103 pieces are available. For instance, the set of 103 pieces consists of the following:

1. One piece of 1.005 mm
2. 49 pieces ranging from 1.01 to 1.49 mm in steps of 0.01 mm

3. 49 pieces ranging from 0.5 to 24.5 mm in steps of 0.5 mm
4. Four pieces ranging from 25 to 100 mm in steps of 25 mm

A set of 56 slip gauges consists of the following:

1. One piece of 1.0005 mm
2. Nine pieces ranging from 1.001 to 1.009 mm in steps of 0.001 mm
3. Nine pieces ranging from 1.01 to 1.09 mm in steps of 0.01 mm
4. Nine pieces ranging from 1.0 to 1.9 mm in steps of 0.1 mm
5. 25 pieces ranging from 1 to 25 mm in steps of 1.0 mm
6. Three pieces ranging from 25 to 75 mm in steps of 25 mm

Generally, the set of slip gauges will also include a pair of tungsten carbide protection gauges. These are marked with letter 'P', are 1 or 1.5 mm thick, and are wrung to the end of the slip gauge combination. They are used whenever slip gauges are used along with instruments like sine bars, which are made of metallic surfaces that may accelerate the wear of regular slip gauges. Wear blocks are also recommended when gauge block holders are used to hold a set of wrung gauges together. The purpose of using a pair of wear blocks, one at the top and the other at the bottom of the stack, is to ensure that major wear is concentrated over the two wear gauges, which can be economically replaced when worn out. This will extend the useful life of the set of slip gauges.

4.9.2 Wringing of Slip Gauges

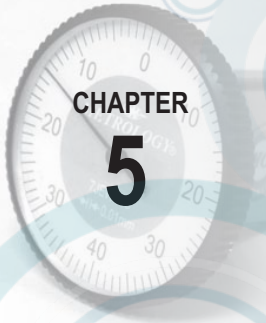
Wringing is the phenomenon of adhesion of two flat and smooth surfaces when they are brought into close contact with each other. The force of adhesion is such that the stack of a set of blocks will almost serve as a single block, and can be handled and moved around without disturbing the position of individual blocks. More importantly, if the surfaces are clean and flat, the thin layer of film separating the blocks will also have negligible thickness. This means that stacking of multiple blocks of known dimensions will give the overall dimension with minimum error.

Wringing Phenomenon

When two surfaces are brought into contact, some amount of space exists between them. This is because of surface irregularities and presence of dirt, oil, grease, or air pockets. Let us assume that the two surfaces are perfectly flat with highly finished surfaces, free from dirt and oil, and firmly pressed together. Now the air gap becomes so small that it acts in the same way as a liquid film. The thickness of this film can be as low as 0.00001 mm. Now a question arises as to why the blocks stick together so firmly that even a high magnitude of force acting perpendicular to their surfaces will not be able to separate them. A combination of two factors appears to ensure this high adhesion force. First, as shown in Fig. 4.43, an atmospheric force of 1 bar is acting in the direction shown by the two arrows. This is contributing to the adhesion of the surfaces of the two slip gauges.

Secondly, the surfaces are in such close proximity that there is molecular adhesion of high magnitude that creates a high adhesion force. Since the slip gauge surfaces undergo lapping as a super finishing operation, material removal takes place at the molecular level. Since some molecules are lost during the lapping operation, the material is receptive to molecules of the mating surface, which creates high molecular adhesion.

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CHAPTER 5

Angular Measurement

After studying this chapter, the reader will be able to

- understand the basic requirements of angular measurement in the industry and the variety of instruments available at our disposal
- elucidate the basic principle of a protractor and its extension as the universal bevel protractor, which is an indispensable part of a metrology laboratory
- measure angles using the sine principle and explain the use of sine bar, sine block, sine plate, and sine centre
- use angle gauges to set them accurately to the required angle
- appreciate the importance of 'bubble instruments' such as the conventional spirit level and clinometers in angular measurement
- explain the principles of optical measurement instruments, the most popular ones being the autocollimator and the angle dekkor

5.1 INTRODUCTION

Length standards such as foot and metre are arbitrary inventions of man. This has necessitated the use of wavelength of light as a reference standard of length because of the difficulty in accurately replicating the earlier standards. On the other hand, the standard for angle, which is derived with relation to a circle, is not man-made but exists in nature. One may call it degree or radian, but the fact remains that it has a direct relation to a circle, which is an envelope of a line moving about one of its ends. Whether one defines a circle as the circumference of a planet or path of an electron around the nucleus of an atom, its parts always bear a unique relationship.

The precise measurement of angles is an important requirement in workshops and tool rooms. We need to measure angles of interchangeable parts, gears, jigs, fixtures, etc. Some of the typical measurements are tapers of bores, flank angle and included angle of a gear, angle made by a seating surface of a jig with respect to a reference surface, and taper angle of a jib. Sometimes, the primary objective of angle measurement is not to measure angles. This may sound rather strange, but this is the case in the assessment of alignment of machine parts. Measurement of straightness, parallelism, and flatness of machine parts requires highly

sensitive instruments like autocollimators. The angle reading from such an instrument is a measure of the error of alignment.

There are a wide range of instruments, starting from simple scaled instruments to sophisticated types that use laser interferometry techniques. The basic types are simple improvisations of a protractor, but with better discrimination (least count), for example, a vernier protractor. These instruments are provided with a mechanical support or a simple mechanism to position them accurately against the given workpiece and lock the reading. A spirit level has universal applications, not only in mechanical engineering but also in civil engineering construction for aligning structural members such as beams and columns. Instruments employing the basic principle of a spirit level but with higher resolution, such as conventional or electronic clinometers, are popular in metrology applications. By far, the most precise instruments are collimators and angle dekkors, which belong to the family of instruments referred to as *optical tooling*. This chapter deals with some of the popular angle measurement devices that are widely used in the industry.

5.2 PROTRACTOR



A simple protractor is a basic device used for measuring angles. At best, it can provide a least count of 1° for smaller protractors and ½° for large ones. However, simple though it may be, the user should follow the basic principles of its usage to measure angles accurately. For instance, the surface of the instrument should be parallel to the surface of the object, and the reference line of the protractor should coincide perfectly with the reference line of the angle being measured. Positioning of the protractor and observation of readings should be performed with care to avoid parallax error.

Similar to a steel rule, a simple protractor has limited usage in engineering metrology. However, a few additions and a simple mechanism, which can hold a main scale, a vernier scale, and a rotatable blade, can make it very versatile. A universal bevel protractor is one such instrument that has a mechanism that enables easy measurement and retention of a reading. A vernier scale improves the least count substantially. Additional attachments enable the measurement of acute and obtuse angles with ease and thereby justify its name as the universal bevel protractor. It can measure the angle enclosed by bevelled surfaces with ease and hence the name.

In fact, if one traces the history of development of angle-measuring devices, the bevel protractor preceded the universal bevel protractor. The earliest bevel protractor had a simple mechanism that facilitated rotation of measuring blades and locked them in place. It had a scale graduated in degrees on which the measurements could be directly read. However, these instruments have largely been replaced by universal bevel protractors and the older types are not being used in metrology applications now. Therefore, we shall directly go to a discussion on the universal bevel protractor.

5.2.1 Universal Bevel Protractor

The universal bevel protractor with a 5' accuracy is commonly found in all tool rooms and metrology laboratories. Figure 5.1 illustrates the construction of a universal bevel protractor. It has a base plate or stock whose surface has a high degree of flatness and surface finish. The stock is placed on the workpiece whose angle is to be measured. An adjustable blade attached

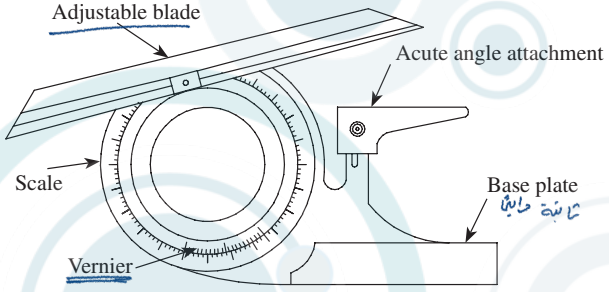


Fig. 5.1 Universal bevel protractor

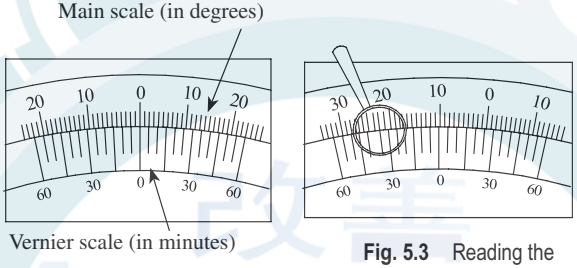


Fig. 5.2 Divisions on the vernier scale

Fig. 5.3 Reading the vernier scale

to a circular dial is made to coincide with the angular surface. It can be swivelled to the required angle and locked into position to facilitate accurate reading of the circular scale that is mounted on the dial. The main scale on the dial is graduated in degrees and rotates with the rotation of the adjustable blade. A stationary vernier scale mounted close to the dial, as shown in Fig. 5.1, enables measurements to a least count of 5' or less. An acute angle attachment is provided for the measurement of acute angles.

The main scale on the dial is divided into four quadrants, each measuring 90°. Each division on this scale reads 1°. The degrees are numbered from 0 to 90 on either side of the zeroth division. The vernier scale has 24 divisions, which correspond to 46 divisions on the main scale. However, the divisions on the vernier scale are numbered from 0 to 60 on either side of the zeroth division, as shown in Fig. 5.2.

Calculation of Least Count

Value of one main scale division = 1°

24 vernier divisions correspond to 46 main scale divisions. From Fig. 5.2, it is clear that one vernier division equals 1/12th of 23°. Let us assume that the zeroth division on both the main and the vernier scales are lined up to coincide with each other. Now, as the dial rotates, a vernier division, starting from the fifth minute up to the 60th minute, progressively coincides with a main scale division until the zeroth division on the vernier scale moves over the main scale by 2°.

Therefore, the least count is the difference between one vernier division and two main scale divisions, which is 1/12° or 5'.

Reading Vernier Scales

Consider the situation shown in Fig. 5.3. The zeroth division of the vernier scale is just past the 10° division on the main scale. The seventh division, marked as the 35' division, on the left-hand side of the vernier scale coincides with a division on the main scale. Therefore, the reading in this case is 10°35'.

Sometimes, confusion arises regarding the direction in which the vernier has to be read. This confusion may crop up for the aforementioned example also. It is possible that a division on the right side of zero on the vernier scale may be coinciding with a division on the main scale (dial scale). In order to eliminate this confusion, we follow a simple rule. *Always read the*

vernier from zero in the same direction that you read the dial scale. In the given example, the 10th division on the dial, which is close to the zeroth division on the vernier, is to the left of the zeroth division on the dial scale. In other words, the dial scale is being read in the leftward or anticlockwise direction. Therefore, the vernier should also be read towards the left of the vernier zero division. Figure 5.4 illustrates the use of a bevel protractor for measurement of angles. While Fig. 5.4(a) illustrates the use of acute angle attachment, Fig. 5.4(b) shows how the angle of an inside bevelled face can be measured.

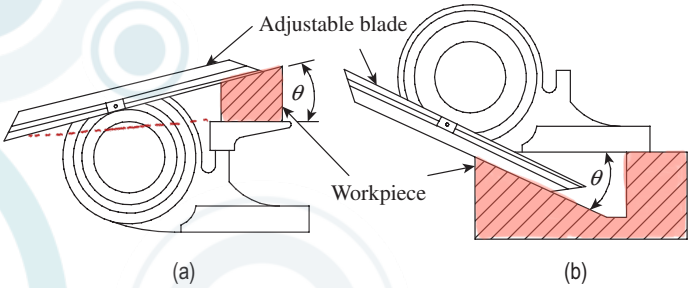


Fig. 5.4 Measurement of angles using bevel protractor (a) Acute angle attachment (b) Inside bevelled face angle measurement

Angles and their Supplements

Since a universal bevel protractor can measure both acute and obtuse angles, care should be exercised to clearly differentiate between the angle being indicated on the scale and its supplement. The dial gauge is graduated from 0° to 90° in four quadrants, as shown in Fig. 5.5. Figure 5.5(a) illustrates the orientation of the blade with respect to the base when the protractor is set to 90°. The zeroth division on the vernier coincides with the 90° division on the dial scale.

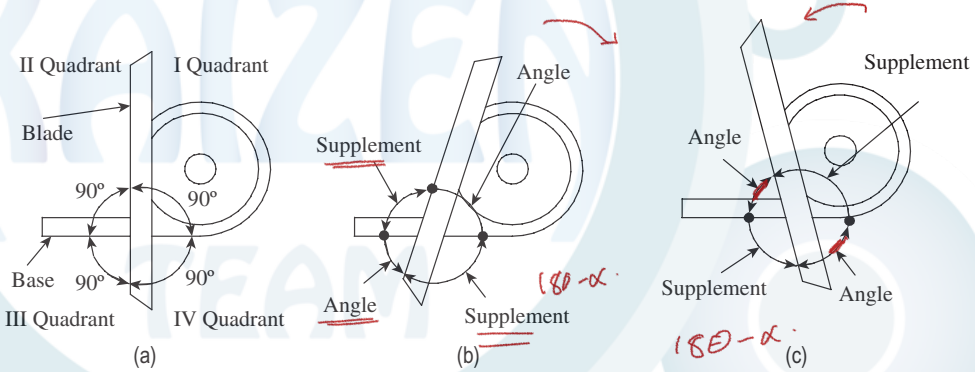


Fig. 5.5 Angles and their supplements (a) Blade oriented with base (b) Blade turned clockwise (c) Blade turned counterclockwise

Suppose the blade is turned clockwise, as in Fig. 5.5(b), the angles read directly are those that are formed from the blade to the base counterclockwise. Thus, if the angles of a work part are being measured in quadrant I or III, the angles can be read directly from the scale. On the other hand, if the angles of a work part are being measured in quadrant II or IV, the actual angles are given by their supplements. In other words, the value of the angle is obtained by subtracting the angle indicated by the scale from 180°. Both these angles, obviously, are obtuse angles.

Further, Fig. 5.5(c) illustrates a situation when the blade is turned counterclockwise. Here also, angles can be directly read only in two quadrants, namely the second and the fourth. These angles are formed in the clockwise direction from the blade to the base, and are acute angles. The supplements in I and III quadrants give the obtuse angles of the work parts, which are held in these quadrants.

Bevel protractors in general are classified into four types: A, B, C, and D. Types C and D are the basic types, with the dial scale graduated in degrees. They are neither provided with a vernier scale nor a fine adjustment device. Types A and B are provided with a vernier scale, which can accurately read up to 5'. While type A has both an acute angle attachment and a fine adjustment device, type B does not have either of them.

A bevel protractor is a precision angle-measuring instrument. To ensure an accurate measurement, one should follow these guidelines:

1. The instrument should be thoroughly cleaned before use. It is not recommended to use compressed air for cleaning, as it can drive particles into the instrument.
2. It is important to understand that the universal bevel protractor does not essentially measure the angle on the work part. It measures the angle between its own parts, that is, the angle between the base plate and the adjustable blade. Therefore, one should ensure proper and intimate contact between the protractor and the features of the part.
3. An easy method to determine if the blade is in contact with the work part is to place a light behind it and adjust the blade so that no light leaks between the two.
4. It should always be ensured that the instrument is in a plane parallel to the plane of the angle. In the absence of this condition, the angle measured will be erroneous.
5. The accuracy of measurement also depends on the surface quality of the work part. Burrs and excessive surface roughness interfere with the intimate contact between the bevel protractor and the work part, leading to erroneous measurements.
6. One should be careful to not slide the instrument over hard or abrasive surfaces, and not over-tighten clamps.
7. Before replacing the instrument in its case, it has to be wiped with a clean and dry cloth, a thin rust-preventing coating has to be applied, and moving parts need to be lubricated.

5.2.2 Optical Bevel Protractor

An optical protractor is a simple extension of the universal bevel protractor. A lens in the form of an eyepiece is provided to facilitate easy reading of the protractor scale. Figure 5.6 illustrates the construction details of an optical bevel protractor. The blade is clamped to the dial by means of a blade clamp. This enables fitting of blades of different lengths, depending on the work part being measured. In a protractor without a vernier, the dial scale reading can be

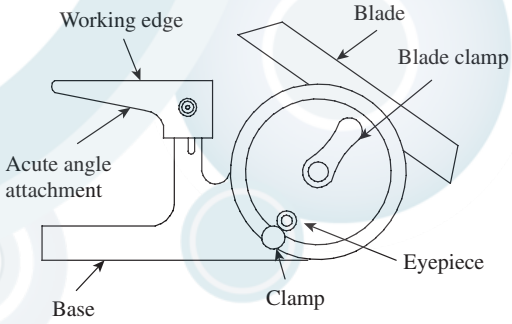


Fig. 5.6 Optical bevel protractor

directly read through the eyepiece. In vernier protractors, the eyepiece is attached on top of the vernier scale itself, which together move as a single unit over the stationary dial scale. The eyepiece provides a magnified view of the reading for the convenience of the user.

Most of the universal protractors in use are of this type. An acute angle attachment is provided to facilitate measurement of acute angles on work parts. A clamp is provided to lock the reading, so that it can be read and recorded at a convenient position by the user.

5.3 SINE BAR

A sine bar is used to measure angles based on the sine principle. Its upper surface forms the hypotenuse of a triangle formed by a steel bar terminating in a cylinder near each end. When one of the cylinders, called a roller, is resting on a flat surface, the bar can be set at any desired angle by simply raising the second cylinder. The required angle is obtained when the difference in height between the two rollers is equal to the sine of the angle multiplied by the distance between the centres of the rollers. Figure 5.7 illustrates the construction details of a sine bar.

Sine bars are made of corrosion-resistant steel, and are hardened, ground, and stabilized. The size is specified by the distance between the centres of the cylinders, which is 100, 200, or 300 mm. The upper surface has a high degree of flatness of up to 0.001 mm for a 100 mm length and is perfectly parallel to the axis joining the centres of the two cylinders. The parallelism of upper surface with the datum line is of the order of 0.001 mm for a 100 mm length. Relief holes are sometimes provided to reduce the weight of the sine bar. This by itself is not a complete measuring instrument. Accessories such as a surface plate and slip gauges are needed to perform the measurement process. Figure 5.8 illustrates the application of a sine rule for angle measurement.

The sine of angle θ formed between the upper surface of a sine bar and the surface plate (datum) is given by

$$\text{Sin}\,(\theta) = h/L$$

where h is the height difference between the two rollers and L is the distance between the centres of the rollers.

Therefore, $h = L\ \text{Sin}\,(\theta)$

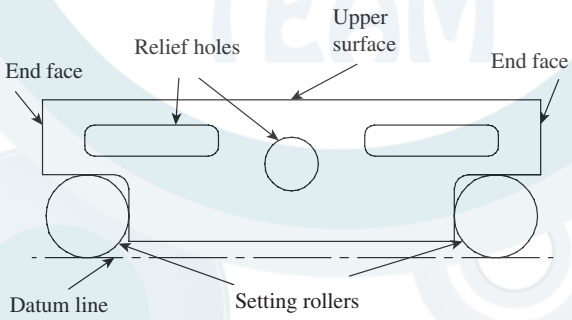


Fig. 5.7 Sine bar

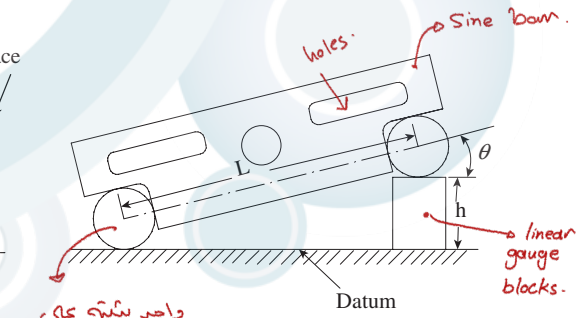


Fig. 5.8 Sine rule

5.3.1 Setting Sine Bars to Desired Angles

By building slip gauges to height h and placing the sine bar on a surface plate with one roller on top of the slip gauges, the upper surface can be set to a desired angle with respect to the surface plate. The set-up is easier because the cylinders are integral parts of the sine bar and no separate clamping is required. No measurement is required between the cylinders since this is a known length. It is preferable to use the sine bar on a grade A surface plate. In addition, it is desirable to support both rollers on gauge blocks so that the minute irregularities of the surface plate may be eliminated.

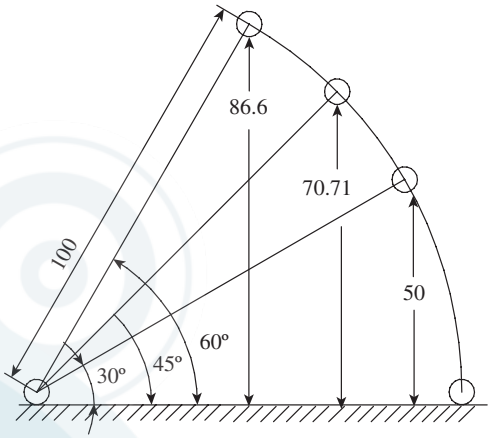


Fig. 5.9 Change in sine value with change in angle

The question often asked is about the maximum angle that can be set using a sine bar. The standard response is 45°. At higher angles, errors due to the distance between the centres of the rollers and gauge blocks get magnified. This is explained in the following example.

Let us assume a 100 mm-long sine bar and calculate the heights to set it at 30°, 45°, and 60°, as shown in Fig. 5.9. The heights are respectively 53, 73.71, and 89.6 mm for angles 30°, 60°, and 90°.

Assume there is an error of +0.1 mm in the height, h. Table 5.1 illustrates the error in the measured angles. The actual angle in 'degrees' is given by $\sin^{-1}(h/L)$.

Table 5.1 Relationship between error and angle being set

Angle to be set (degrees)	Length of sine bar (mm)	Height of slip gauges (mm)	Actual angle (degrees)	Error in measurement (degrees)
30	100.0	50	30	0.066
		50.1	30.066	
45	100.0	70.71	45	0.080
		70.81	45.080	
60	100.0	86.6	60	0.112
		86.7	60.112	

Accounting for an error of 0.1 mm in height h, the angular error for 30° is 0.066 mm. This error increases to 0.08 mm for 45° and jumps to 0.112 mm for 60°. A similar increase in error is observed if the distance between the centres of the rollers of the sine bar has an error. This is the primary reason why metrologists avoid using sine bars for angles greater than 45°.

5.3.2 Measuring Unknown Angles with Sine Bar

A sine bar can also be used to measure unknown angles with a high degree of precision. The angle of the work part is first measured using an instrument like a bevel protractor. Then, the work part is clamped to the sine bar and set on top of a surface plate to that angle using slip gauges, as shown in Fig. 5.10 (clamping details are not shown in the figure).

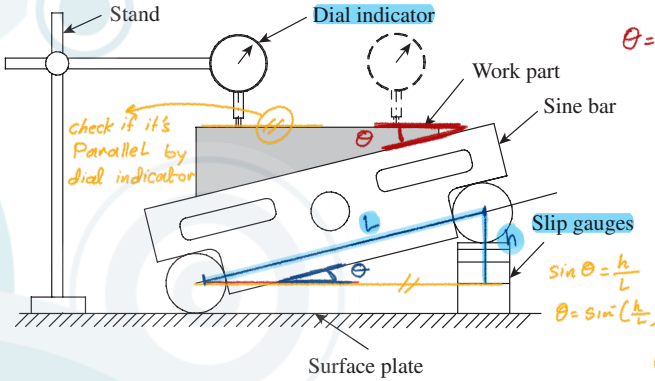


Fig. 5.10 Measurement of unknown angles

A dial gauge fixed to a stand is brought in contact with the top surface of the work part at one end and set to zero. Now, the dial indicator is moved to the other end of the work part in a straight line. A zero reading on the dial indicator indicates that the work part surface is perfectly horizontal and the set angle is the right one. On the other hand, if the dial indicator shows any deviations, adjustments in the height of slip gauges is necessary to ensure that the work part surface is horizontal. The difference in height corresponding to the dial gauge reading is incorporated in the slip gauges, and the procedure is repeated until the dial indicators show zero deviation. The actual angle is calculated using the total height of the slip gauges.

Instead of a dial gauge, a high-amplification comparator can be used for better accuracy. Whether setting a sine bar to a known angle or for measuring unknown angles, a few guidelines should be followed to ensure proper usage of the instrument:

1. It is not recommended to use sine bars for angles greater than 45° because any error in the sine bar or height of slip gauges gets accentuated.
2. Sine bars provide the most reliable measurements for angles less than 15°.
3. The longer the sine bar, the better the measurement accuracy.
4. It is preferable to use the sine bar at a temperature recommended by the supplier. The accuracy of measurement is influenced by the ambient temperature.
5. It is recommended to clamp the sine bar and the work part against an angle plate. This prevents misalignment of the workpiece with the sine bar while making measurements.
6. One should always keep in mind that the sine principle can be put to use provided the sine bar is used along with a high-quality surface plate and set of slip gauges.

5.3.3 Sine Blocks, Sine Plates, and Sine Tables

A *sine block* is a sine bar that is wide enough to stand unsupported (Fig. 5.11). If it rests on an integral base, it becomes a *sine plate* (Fig. 5.12). A sine plate is wider than a sine block. A heavy-duty sine plate is rugged enough to hold work parts for machining or inspection of angles. If a sine plate is an integral part of another device, for example, a machine tool, it is called a *sine table*. However, there is no exact dividing line between the three.

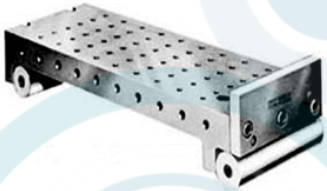


Fig. 5.11 Sine block



Fig. 5.12 Sine plate

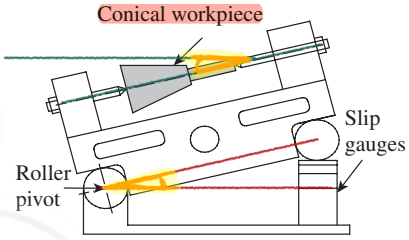


Fig. 5.13 Sine centre

In all these three devices, the work part rests on them. They are often used like a fixture to keep the work part at a particular orientation, so that the required angle is machined. The instruments have attachments to raise and lock the block to the required angle, and to also fasten work parts. The sine table is the most rugged device, which may be swung to any angle from 0° to 90° by pivoting about the hinged end.

There are many instances where compound angles need to be machined or inspected. While simple angles lie on one plane, compound angles of a surface lie on more than one plane. In a surface formed by the intersections of planes, the angles on the surface planes are called *face angles*. A compound sine plate can conveniently measure or set itself to this face angle. In a typical compound sine plate, there are two sine plates: a base plate creates one plane, while the top plate creates the second plane. Compound sine plates are usually used for finishing operations, for example, a finish grinding operation.

5.3.4 Sine Centre

A sine centre provides a convenient means of measuring angles of conical workpieces that are held between centres, as shown in Fig. 5.13. One of the rollers is pivoted about its axis, thereby allowing the sine bar to be set to an angle by lifting the other roller. The base of the sine centre has a high degree of flatness, and slip gauges are wrung and placed on it to set the sine bar at the required angle.

Conical workpieces that need to be inspected are placed between the centres. The sine centre is used for measuring angles up to 60°. The procedure for measuring angles is very similar to the one described in Section 5.3.2. A dial gauge clamped to a stand is set against the conical workpiece. The sine bar is set to an angle such that the dial gauge registers no deviation when moved from one end of the workpiece to the other. The angle is determined by applying the sine rule.

5.4 ANGLE GAUGES

Angle gauges, which are made of high-grade wear-resistant steel, work on a principle similar to slip gauges. While slip gauges can be built to give linear dimensions, angle gauges can be built to give the required angle. The gauges come in a standard set of angle blocks that can be wrung together in a suitable combination to build an angle. C.E. Johansson, who developed slip gauges, is also credited with the invention of angle gauge blocks. However, the first set of a combination of angle gauges was devised by Dr G.A. Tomlinson of the National Physical

Laboratory, UK, in the year 1939, which provided the highest number of angle combinations. His set of 10 blocks can be used to set any angle between 0° and 180° in increments of 5'.

At the outset, it seems improbable that a set of 10 gauges is sufficient to build so many angles. However, angle blocks have a special feature that is impossible in slip gauges—the former can be subtracted as well as added. This fact is illustrated in Fig. 5.14.

This illustration shows the way in which two gauge blocks can be used in combination to generate two different angles. If a 5° angle block is used along with a 30° angle block, as shown in Fig. 5.14(a), the resulting angle is 35°. If the 5° angle block is reversed and combined with the 30° angle block, as shown in Fig. 5.14(b), the resulting angle is 25°. Reversal of an angle block subtracts itself from the total angle generated by combining other angle blocks. This provides the scope for creating various combinations of angle gauges in order to generate angles that are spread over a wide range by using a minimum number of gauges.

Angle gauges are made of hardened steel, which is lapped and polished to a high degree of accuracy and flatness. The gauges are about 75 mm long and 15 mm wide, and the two surfaces that generate the angles are accurate up to ±2". The gauges are available in sets of 6, 11, or 16. Table 5.2 provides the details of individual blocks in these sets.

Most angles can be combined in several ways. However, in order to minimize error, which gets compounded if the number of gauges used is increased, it is preferable to use the least number of angle gauge blocks. The set of 16 gauges forms all the angles between 0° and 99° in 1" steps—a total of 3,56,400 combinations! The laboratory master-grade set has an accuracy of one-fourth of a second. While the inspection-grade set has an accuracy of ½", the tool room-grade set has an accuracy of 1".

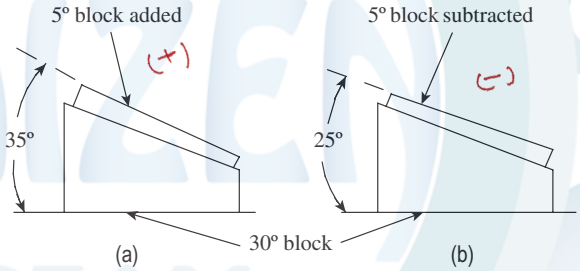


Fig. 5.14 Angle gauge block (a) Addition (b) Subtraction

Table 5.2 Angle gauge block sets

Smallest increment by which any angle can be produced	Number of individual blocks contained in the set	Detailed listing of the blocks composing the set
1°	6	Six blocks of 1°, 3°, 5°, 15°, 30°, and 45°
1′	11	Six blocks of 1°, 3°, 5°, 15°, 30°, and 45° Five blocks of 1', 3', 5', 20', and 30′
1″	16	Six blocks of 1°, 3°, 5°, 15°, 30°, and 45° Five blocks of 1', 3', 5', 20', and 30' Five blocks of 1", 3", 5", 20", and 30"

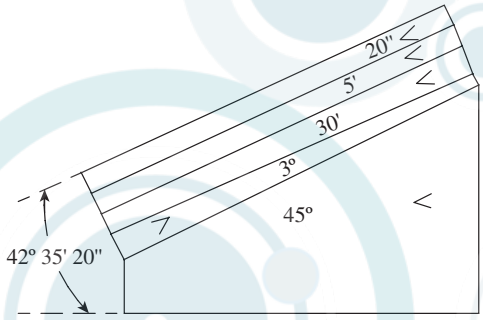


Fig. 5.15 Combination of angle gauges for 42°35′20"

The illustrations in Fig. 5.15 show how angle gauges can be combined to provide the required angles. It may be noted that each angle gauge is engraved with the symbol '<', which indicates the direction of the included angle. Obviously, when the angles of the gauges need to be added up, the symbol < of all gauges should be in line. On the other hand, whenever an angle gauge is required to be subtracted from the combination, the gauge should be wrung such that the symbol < is in the other direction.

Let us consider an angle 42°35′20", which is to be built using the 16-gauge set. Starting from degrees, the angle of 42° can be built by subtracting a 3° block from a 45° block. The angle of 35' can be obtained by combining a 30' gauge with a 5' gauge. A 20" gauge is readily available. The resulting combination is shown in Fig. 5.15.

It can be noticed in this combination that except for the 3° angle gauge, all other gauges are added. Accordingly, the 3° gauge is reversed and wrung with the other gauges, as shown in the figure. The 'wringing' method is the same as that of slip gauges explained in Chapter 4. After wringing, the entire combination is placed on a surface plate and the edges are properly aligned to facilitate measurement.

From the calibration point of view, it is much easier to calibrate angle gauge blocks compared to slip gauges. This is due to the fact that an angle being measured is a portion of a full circle and is, therefore, self-proving. For instance, each of three exactly equal portions of 90° must equal 30°. Thus, the breakdown system can be used to create masters of angle measuring, and each combination can be proved by the same method. In addition, the accuracy of angle gauges is not as sensitive to temperature changes as that of slip gauges. For example, a gauge block manufactured at, say, 30 °C will retain the same angle when used at 40 °C, assuming that the readings are taken some time after the temperature has stabilized and the whole body of the gauge is exposed to the same temperature.

5.4.1 Uses

Angle gauges are used for measurement and calibration purposes in tool rooms. It can be used for measuring the angle of a die insert or for inspecting compound angles of tools and dies. They are also used in machine shops for either setting up a machine (e.g., the revolving centre of a magnetic chuck) or for grinding notches on a cylindrical grinding machine. The illustration in Fig. 5.16 highlights the inspection of a compound angle by using angle gauge blocks. In this case, a surface is inclined in two planes at an angle of 90° to each other. Angle gauges offer a simple means for inspecting such a compound angle by using a dial gauge mounted on a stand.

Figure 5.16 shows a workpiece with a compound angle. Let us assume that the back angle (α) is 15°20' and the side angle (β) is 5°. In order to set the workpiece to 15°20', two angle gauge blocks of 15° and 20' are selected and wrung together. This combination is placed on a surface plate, and the workpiece is positioned on top of the angle gauges. Now, the dial indicator

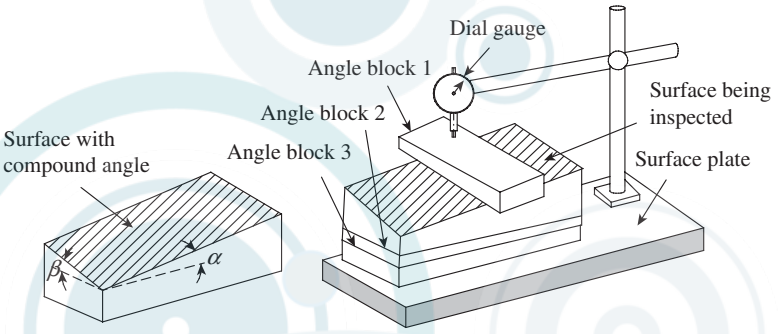


Fig. 5.16 Inspection of a compound angle using angle gauges

reading is taken along a longitudinal direction. If the reading remains zero, it indicates a conformance of the angle α; in this case, the back angle is 15°20'. Then, a 5° angle block is selected and is positioned across the workpiece in the transverse direction, as shown in the figure. Correctness of the compound angle is then easily determined by running the dial indictor across the top surface of the 5° gauge in the transverse direction. A zero reading on the dial gauge indicates the conformance of angle β, that is, 5°. Thus, in a single setting, the compound angles can be inspected using simple devices.

5.4.2 Manufacture and Calibration

Angle gauges are quite often used as the standard for calibration purpose, and therefore, should be manufactured with a high degree of accuracy and precision. Steel blanks are cut to the required shape and machined to the nearest size and shape. Before subjecting them to finish machining, the blanks are heat treated to impart the required hardness. The heat treatment process involves quenching and tempering, followed by a stabilizing process. Now, the gauges are ground and lapped using a sine table. The advantage of using a sine table is that it can ensure that a precise angle is generated without needing to use a custom-made jig or fixture. The non-gauging sides of an angle block are ground and lapped to uniform thickness. This is followed by lapping of the gauging faces. It is important to ensure that the gauging faces are perfectly square to the non-gauging sides. The gauges are then inspected using an autocollimator or interferometry technique to ensure that they meet the accuracy requirements.

The newly manufactured or in-use angle gauges are subjected to calibration to ensure accuracy. One of the popular calibration methods for angle gauges is the interferometry method, which is quite a simple and accurate way of calibrating angle gauges.

The angle gauge, which needs to be calibrated, is carefully placed on a steel platen. The platen is nothing but a surface plate with a degree of flatness. An optical flat is positioned above the angle gauge at some angle, as shown in Fig. 5.17. A monochromatic light source is provided for the optical flat, so that fringe patterns are seen on both the platen and the angle gauge. Assuming that the angle gauge and the platen surfaces are inclined in one plane only, the fringes are straight, parallel, and equally spaced. However, the pitch of the two sets of fringes is different; those on the angle gauge have a lesser pitch. For a distance 'l' measured across the fringes, if 'p' is the number of fringes on the platen and 'q' the number of fringes on the angle gauge, then,

$$\theta = \theta_1 + \theta_2 = \lambda\,(p - q)/2l$$

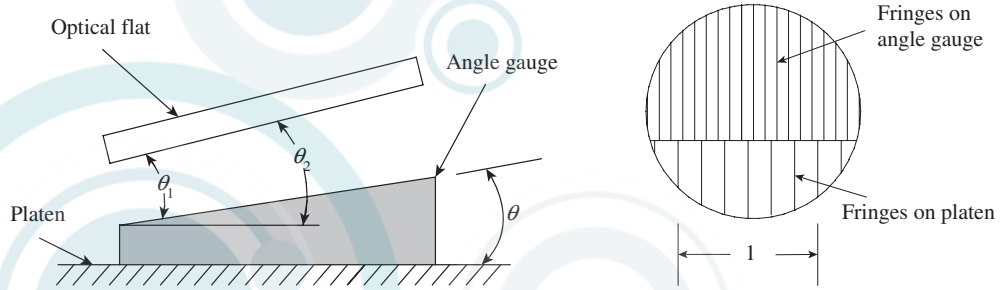


Fig. 5.17 Calibration of angle gauges by interferometry

where λ is the wavelength of light. In this method, it is possible to calibrate angle gauges up to 0.1" of an arc.

5.4.3 True Square

A true square is used as a companion tool along with an angle gauge block set. It is available for both tool room and laboratory master sets. As the name itself suggests, it is a square piece made of hardened and wear-resistant steel. All faces of the true square are precisely at a 90° angle to adjacent gauging surfaces. It has a high degree of optical flatness and parallelism to be used with autocollimators. The main advantage of a true square is that it extends the range of the angle block set to 360°, be it in degree, minute, or second steps. Figure 5.18 illustrates the shape of a true square.

5.5 SPIRIT LEVEL

A spirit level is a basic 'bubble instrument', which is widely used in engineering metrology. It is derived from the practice in cold western countries. To combat freezing, the tubes were filled with 'spirits of wine', hence the general term spirit level. Spirit level, as you are aware, is an angular measuring device in which the bubble always moves to the highest point of a glass vial. The details of a typical spirit level are shown in Fig. 5.19. The base, called the reference plane, is seated on the machine part for which straightness or flatness is to be determined. When the base is horizontal, the bubble rests at the centre of the graduated scale, which is engraved on the glass. When the base of the spirit level moves out of the horizontal, the bubble shifts to the highest point of the tube. The position of the bubble with reference to the scale is a measure of the angularity of the machine part. This scale is calibrated to directly provide the reading in minutes or seconds. A cross test level provided at a right angle to the main bubble scale indicates the inclination in the other plane. A screw adjustment is provided to set the bubble to zero by referencing with a surface plate.

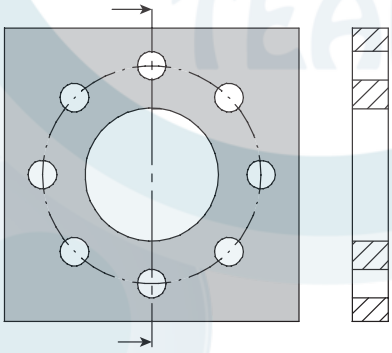


Fig. 5.18 True square

The performance of the spirit level is governed by the

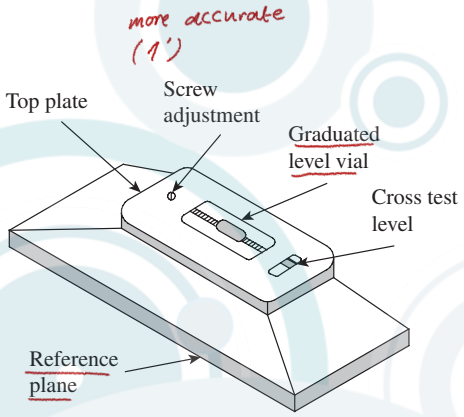


Fig. 5.19 Spirit level

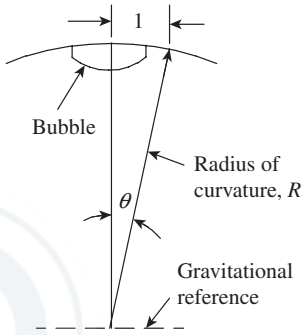


Fig. 5.20 Relationship between radius of curvature and bubble scale reading

geometrical relationship between the bubble and the two references. The first reference is the effect of gravity acting at the centre of the bubble. The second is the scale against which the bubble position is read. The sensitivity of the spirit level depends on the radius of curvature of the bubble, which is formed against the inside surface of the glass vial, and the base length of its mount.

Assuming that a level has graduations on the vial with a least count of 1 mm and a radius of curvature, R, as shown in Fig. 5.20, the angle $\theta = l/R$ (since θ is very small).

If the graduations are at a 2 mm interval and represent a tilt of 10", then the following can be concluded:

$$\theta^c = 10 \times \pi/(180 \times 3600)$$

Therefore, $R = 41{,}273.89$ mm or 41.274 m approximately.

If the base length is 250 mm, the height h, to which one end must be raised for a 2 mm bubble movement, is given by the following relation:

$$\theta^c = h/250$$

Therefore, $h = 0.012$ mm.

It is obvious from these computations that sensitivity of the instrument depends on the radius of curvature of the bubble tube and the base length. Sensitivity can be increased by either increasing the radius of curvature or reducing the base length. The most useful sensitivity for precision measurement is 10" per division.

The main use of a spirit level is not for measuring angles, but for measuring alignment of machine parts and determining flatness and straightness. Typically, the level is stepped along the surface in intervals of its own base length, the first position being taken as the datum. The heights of all other points are determined relative to this datum. One should always keep in mind that the accuracy of a given spirit level depends on the setting of the vial relative to the base. There is bound to be a certain amount of error in the setting of the vial. In order to minimize this error, the following procedure is recommended while using a spirit level for precision measurement:

1. Take readings from both ends of the vial.
2. Reverse the base of the spirit level.
3. Repeat readings from both ends.

4. Average the four readings.
5. Repeat all steps for critical cases.

more accurate than the Spirit level.

5.5.1 Clinometer

A clinometer (Fig. 5.21) is a special case of a spirit level. While the spirit level is restricted to relatively small angles, clinometers can be used for much larger angles. It comprises a level mounted on a frame so that the frame may be turned to any desired angle with respect to a horizontal reference. Clinometers are used to determine straightness and flatness of surfaces. They are also used for setting inclinable tables on jig boring machines and angular jobs on surface grinding machines. They provide superior accuracy compared to ordinary spirit levels.

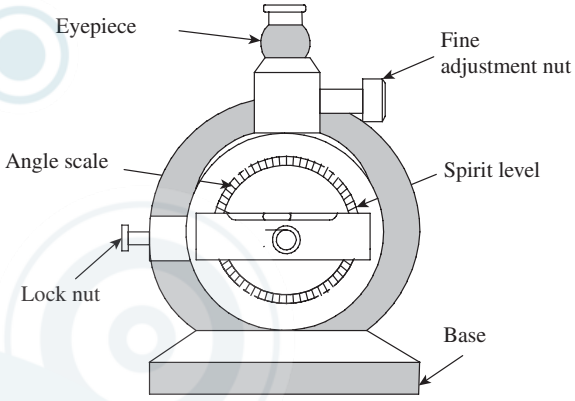


Fig. 5.21 Clinometer

To measure with clinometers, the base is kept on the surface of the workpiece. The lock nut is loosened, and the dial comprising the circular scale is gently rotated until the bubble in the spirit level is approximately at the centre. Now, the lock nut is tightened and the fine adjustment nut is operated until the bubble is exactly at the centre of the vial scale. The reading is then viewed through the eyepiece. Most clinometers in a metrology laboratory provide readings up to an accuracy of 1'. Precision clinometers can be used if the accuracy requirement is up to 1".

A recent advancement in clinometers is the electronic clinometer. It consists of a pendulum whose displacement is converted into electrical signals by a linear voltage differential transformer. This provides the advantage of electronic amplification. It is powered by an electronic chip that has a provision for recording and data analysis. Electronic clinometers have a sensitivity of 1". A major advantage of these clinometers is that the readings settle down within 1 second in contrast to the mechanical type, which requires a couple of seconds for the reading to settle down.

5.6 OPTICAL INSTRUMENTS FOR ANGULAR MEASUREMENT

Chapter 7 is devoted to the discussion of optical measurements. Nevertheless, it would be appropriate to highlight the four principles that govern the application of optics in metrology here. The most vital one is *magnification*, which provides visual enlargement of the object. Magnification enables easy and accurate measurement of the attributes of an object. The second one is *accuracy*. A monochromatic light source provides the absolute standard of length, and therefore, ensures a high degree of accuracy. The third principle is one of *alignment*. It uses light rays to establish references such as lines and planes. The fourth, and a significant one, is the principle of *interferometry*, which is a unique phenomenon associated with light. These principles have driven the development of a large number of measuring instruments and comparators. This section is devoted to two such instruments, which are most popular in angular measurement, namely the autocollimator and the angle dekkor.

An autocollimator is an optical instrument that is used to measure small angles with very

Chapter (5) : Angular measurement.

* primary objective ⇝ measure the straightness, parallelism, & Flatness ⇝ require sensitive instruments as autocollimators

the angle reading = measure of the error.

(5.2) Protractor : least count 1° in small protractor
& $\frac{1}{2}$° " large "

↳ parallel to the object

* limited usage ⇝ not accurate

→ Universal Bevel protractor : ⇝ accuracy = 5′
with base plate, high degree of Flatness ... ①

② Blade, swivelled to required angles ⇝ rotate with the main scale.

③ Main Scale : 4 quardants 1° from (0°–90°)

④ Vernier Scale : 24 divisions (1′–60′)

⇝ لرفع قراءة الزاوية الحادة between base & blade.

→ Angles & their Supplements :

α : Acute angle ⟹ between base & blade
θ : Supplements ⟹ 180 − α

α = 15° 45′
the Supplements
θ = 164° 15′

** Optical bevel protractor

①

(5.3) Sine bars : more accurate reading ⇝ required angle ⇒ difference between the two rollers = Sinθ * L.

↳ made of corrosion resistance steel ⇝ with holes = Less weight

* not complete measuring → indirect.

⇒ $\sin\theta = \frac{h}{L}$ ⇝ $\theta = \sin^{-1}\left(\frac{h}{L}\right)$.

θ: Between the upper surface & the Surface plate (Datum)

② measuring unknow angles

↳ first measured could be with bevel protractor, then sine bar with dial gauge ⇝ check if the surface is perfectly horizontal. (parallel)

+ h : hight using slip gauges

→ Sine blocks : Sine bar wide enough to stand unsupported ⇝ sine plate if it rest on integral base (wider)

↳ heavy-duty, rugged enough to hold work parts

Sine table : if sine plate is an integral part of other devices

*** Sine Center for conical workpieces

(5.4) Angular gauges made of high grade wear resistance steel

* two gauge blocks can generate two different angles

5′ along 30′ ⟹ 35′
5′ reversed 30′ ⇒ 25′

** True Square : companion tool along angle gauge block

↳ made of hardened & wear resistant steel ⟶ All faces at 90°

⟶ main advantage : extends the range of the angle block set to 360°

Example : 16 pieces set to form 12° 37′ 13″

12° 37′ 13′
+ 30″
+ 20″
− 3″
12° 38″ — 3 blocks

12° 37′ 13″
− 3″
− 30″
+ 20″
12° 37′ — 3 blocks

12° 38′
+ 20′
+ 5′
− 3
13°
− 15°
+ 3°
− 1°
0 — 3 blocks

12° 38′
− 30′
− 5′
− 3′
12°
− 15°
+ 3°
0 — 3 blocks

12° 37′
+ 3′
+ 20′
13°
− 15°
+ 3°
− 1°
0 — 2 blocks + 3 blocks

12° 37′
− 30′
− 5′
− 3′
+ 1′
12°
− 15°
+ 3°
0 — 4 blocks + 2 blocks

9 blocks = 8 blocks = 8 blocks = 9 blocks

(5.5) Spirit Level :

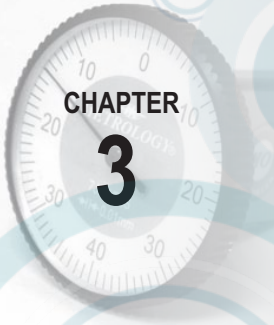
* base (reference) seated on the machine part ⟶ (Straightness or Flatness is to be determined)

↳ horizontal ⟹ bubble rests at the center ⟶ position of the bubble measure the angularity

accuracy = 1′

** Clinometer case of a spirit level ⟿ used for larger angles

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CHAPTER 3

Limits, Fits, and Tolerances

After studying this chapter, the reader will be able to

- understand the importance of manufacturing components to specified sizes
- elucidate the different approaches of interchangeable and selective assembly
- appreciate the significance of different types of limits, fits, and tolerances in design and manufacturing fields, which are required for efficient and effective performance of components/products
- utilize the principle of limit gauging and its importance in inspection in industries
- design simple GO and NOT gauges used in workshops/inspection

3.1 INTRODUCTION

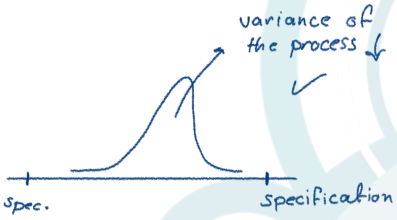
Although any two things found in nature are seldom identical, they may be quite similar. This is also true in the case of manufacturing of different components for engineering applications. No two parts can be produced with identical measurements by any manufacturing process. A manufacturing process essentially comprises five m's—man, machine, materials, money, and management.

Variations in any of the first three elements induce a change in the manufacturing process. All the three elements are subjected to natural and characteristic variations. In any production process, regardless of how well it is designed or how carefully it is maintained, a certain amount of natural variability will always exist. These natural variations are random in nature and are the cumulative effect of many small, essentially uncontrollable causes. When these natural variations in a process are relatively small, we usually consider this to be an acceptable level of process performance.

Usually, variability arises from improperly adjusted machines, operator error, tool wear, and/or defective raw materials. Such characteristic variability is generally large when compared to the natural variability. This variability, which is not a part of random or chance cause pattern, is referred to as 'assignable causes'. Characteristic variations can be attributed to assignable causes that can easily be identified and controlled. However, this has to be

achieved economically, which brings in the fourth element. Characteristic variability causes variations in the size of components. If the process can be kept under control, that is, all the assignable and controllable causes of variations have been eliminated or controlled, the size variations will be well within the prescribed limits. These variations can be modified through operator or management action.

Production processes must perform consistently to meet the production and design requirements. In order to achieve this, it is essential to keep the process under control. Thus, when the process is under control, distribution of most of the measured values will be around the mean value in a more or less symmetrical way, when plotted on a chart. It is therefore impossible to produce a part to an exact size or basic size and some variations, known as tolerances, need to be allowed. Some variability in dimension within certain limits must be tolerated during manufacture, however precise the process may be. The permissible level of tolerance depends on the functional requirements, which cannot be compromised.



No component can be manufactured precisely to a given dimension; it can only be made to lie between two limits, upper (maximum) and lower (minimum). The designer has to suggest these tolerance limits, which are acceptable for each of the dimensions used to define shape and form, and ensure satisfactory operation in service. When the tolerance allowed is sufficiently greater than the process variation, no difficulty arises. The difference between the upper and lower limits is termed *permissive tolerance.*

For example, a shaft has to be manufactured to a diameter of 40 ± 0.02 mm. This means that the shaft, which has a basic size of 40 mm, will be acceptable if its diameter lies anywhere between the limits of sizes, that is, an upper limit of 40.02 mm and a lower limit of 39.98 mm. Then permissive tolerance is equal to 40.02 – 39.98 = 0.04. *Basic* or *nominal size* is defined as the size based on which the dimensional deviations are given.

In any industry, a manufactured product consists of many components. These components when assembled should have a proper fit, in order for the product to function properly and have an extended life. Fit depends on the correct size relationships between the two mating parts. Consider the example of rotation of a shaft in a hole. Enough clearance must be provided between the shaft and the hole to allow an oil film to be maintained for lubrication purpose. If the clearance is too small, excessive force would be required to rotate the shaft. On the other hand, if the clearance is too wide, there would be vibrations and rapid wear resulting in ultimate failure. Therefore, the desired clearance to meet the requirements has to be provided. Similarly, to hold the shaft tightly in the hole, there must be enough interference between the two so that forces of elastic compression grip them tightly and do not allow any relative movement between them.

An ideal condition would be to specify a definite size to the hole and vary the shaft size for a proper fit or vice versa. Unfortunately, in practice, particularly in mass production, it is not possible to manufacture a part to the exact size due to the inherent inaccuracy of manufacturing methods. Even if a part is manufactured to the exact size by chance, it is not possible to measure it accurately and economically during machining. In addition, attempts to manufacture to the exact size can increase the production cost.

Dimensional variations, although extremely small, do exist because of the inevitable inaccuracies in tooling, machining, raw material, and operators. If efforts are made to identify and reduce or eliminate common causes of variation, that is, if the process is kept under control, then the resultant frequency distribution of dimensions produced will have a normal

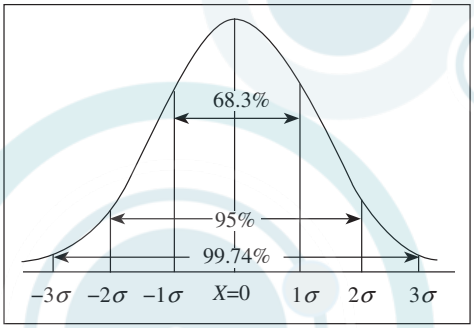


Fig. 3.1 Normal or Gaussian frequency distribution

or Gaussian distribution, that is, 99.74% parts will be well within $\pm 3\sigma$ limits of the mean value, as shown in Fig. 3.1. Thus, it is possible to express the uncertainty in measurement as a multiple of standard deviation. This value is determined by the probability that a measurement will fall outside the stated limits.

3.2 PRINCIPLE OF INTERCHANGEABILITY

For manufacturing a large number of components, it is not economical to produce both the mating parts (components) using the same operator. Further, such parts need to be manufactured within minimum possible time without compromising on quality. To enable the manufacture of identical parts, mass production, an idea of the last industrial revolution that has become very popular and synonymous with the present manufacturing industry, becomes inevitable.

Modern production techniques require that a complete product be broken into various component parts so that the production of each part becomes an independent process, leading to specialization. The various components are manufactured in one or more batches by different persons on different machines at different locations and are then assembled at one place.

To achieve this, it is essential that the parts are manufactured in bulk to the desired accuracy and, at the same time, adhere to the limits of accuracy specified. Manufacture of components under such conditions is called *interchangeable manufacture*.

When interchangeable manufacture is adopted, any one component selected at random should assemble with any other arbitrarily chosen mating component. In order to assemble with a predetermined fit, the dimensions of the components must be confined within the permissible tolerance limits. By *interchangeable assembly*, we mean that identical components, manufactured by different operators, using different machine tools and under different environmental conditions, can be assembled and replaced without any further modification during the assembly stage and without affecting the functioning of the component when assembled. Production on an interchangeable basis results in an increased productivity with a corresponding reduction in manufacturing cost. Modern manufacturing techniques that complement mass production of identical parts facilitating interchangeability of components have been developed. When components are produced in bulk, unless they are interchangeable, the purpose of mass production is not fulfilled.

For example, consider the assembly of a shaft and a part with a hole. The two mating parts are produced in bulk, say 1000 each. By interchangeable assembly any shaft chosen randomly should assemble with any part with a hole selected at random, providing the desired fit.

Another major advantage of interchangeability is the ease with which replacement of defective or worn-out parts is carried out, resulting in reduced maintenance cost. In addition, the operator, by performing the same limited number of operations, becomes a specialist in that work. By achieving specialization in labour, there will be a considerable reduction in manufacturing and assembly time and enhancement in quality. Interchangeable manufacture increases productivity and reduces production and time costs.

In order to achieve interchangeability, certain standards need to be followed, based on which interchangeability can be categorized into two types—universal interchangeability and local interchangeability.

When the parts that are manufactured at different locations are randomly chosen for assembly, it is known as universal interchangeability. To achieve universal interchangeability, it is desirable that common standards be followed by all and the standards used at various manufacturing locations be traceable to international standards.

When the parts that are manufactured at the same manufacturing unit are randomly drawn for assembly, it is referred to as local interchangeability. In this case, local standards are followed, which in turn should be traceable to international standards, as this becomes necessary to obtain the spares from any other source.

3.2.1 Selective Assembly Approach

Today's consumers desire products that are of good quality and, at the same time, reliable and available at attractive prices. Further, in order to achieve interchangeability, it is not economical to manufacture parts to a high degree of accuracy. It is equally important to produce the part economically and, at the same time, maintain the quality of the product for trouble-free operation. Sometimes, for instance, if a part of minimum limit is assembled with a mating part of maximum limit, the fit obtained may not fully satisfy the functional requirements of the assembly. The reason may be attributed to the issues of accuracy and uniformity that may not be satisfied by the certainty of the fits given under a fully interchangeable system. It should be realized that, in practice, complete interchangeability is not always feasible; instead, selective assembly approach can be employed. Attaining complete interchangeability in these cases involves some extra cost in inspection and material handling, as selective assembly approach is employed wherein the parts are manufactured to wider tolerances. In selectively assembly, despite being manufactured to rather wide tolerances, the parts fit and function as if they were precisely manufactured in a precision laboratory to very close tolerances.

The issue of clearances and tolerances when manufacturing on an interchangeable basis is rather different from that when manufacturing on the basis of selective assembly. In interchangeability of manufacture, minimum clearance should be as small as possible as the assembling of the parts and their proper operating performance under allowable service conditions. Maximum clearance should be as great as the functioning of the mechanisms permits. The difference between maximum clearance and minimum clearance establishes the sum of the tolerances on companion parts. To manufacture the parts economically on interchangeable basis, this allowable difference must be smaller than the normal permissible manufacturing conditions. In such situations, selective assembly may be employed. This method enables economical manufacture of components as per the established tolerances. In selective assembly, the manufactured components are classified into groups according to their sizes. Automatic gauging is employed for this purpose. Both the mating parts are segregated according to their sizes, and only matched groups of mating parts are assembled. This ensures complete protection and elimination of defective assemblies, and the matching costs are reduced because the parts are produced with wider tolerances.

Selective assembly finds application in aerospace and automobile industries. A very pertinent and practical example is the manufacture and assembly of ball and bearing units, as the

tolerances desired in such industries are very narrow and impossible to achieve economically by any sophisticated machine tools. Balls are segregated into different groups depending on their size to enable the assembly of any bearing with balls of uniform size. In a broader sense, a combination of both interchangeable and selective assemblies exists in modern-day manufacturing industries, which help to manufacture quality products.

3.3 TOLERANCES

To satisfy the ever-increasing demand for accuracy, the parts have to be produced with less dimensional variation. Hence, the labour and machinery required to manufacture a part has become more expensive. It is essential for the manufacturer to have an in-depth knowledge of the tolerances to manufacture parts economically but, at the same time, adhere to quality and reliability aspects. In fact, precision is engineered selectively in a product depending on the functional requirements and its application. To achieve an increased compatibility between mating parts to enable interchangeable assembly, the manufacturer needs to practise good tolerance principles. Therefore, it is necessary to discuss some important principles of tolerances that are usually employed for manufacturing products.

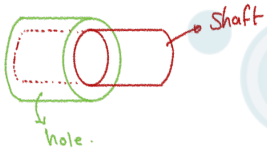
We know that it is not possible to precisely manufacture components to a given dimension because of the inherent inaccuracies of the manufacturing processes. The components are manufactured in accordance with the permissive tolerance limits, as suggested by the designer, to facilitate interchangeable manufacture. The permissible limits of variations in dimensions have to be specified by the designer in a logical manner, giving due consideration to the functional requirements. The choice of the tolerances is also governed by other factors such as manufacturing process, cost, and standardization.

Tolerance can be defined as the magnitude of permissible variation of a dimension or other measured value or control criterion from the specified value. It can also be defined as the total variation permitted in the size of a dimension, and is the algebraic difference between the upper and lower acceptable dimensions. It is an absolute value.

The basic purpose of providing tolerances is to permit dimensional variations in the manufacture of components, adhering to the performance criterion as established by the specification and design. If high performance is the sole criterion, then functional requirements dictate the specification of tolerance limits; otherwise, the choice of setting tolerance, to a limited extent, may be influenced and determined by factors such as methods of tooling and available manufacturing equipment. The industry follows certain approved accuracy standards, such as ANSI (American National Standards Institute) and ASME (American Society of Mechanical Engineers), to manufacture different parts.

3.3.1 Computer-aided Modelling

Nowadays, computers are widely being employed in the design and manufacture of parts. Most leading design tools such as AEROCADD, AUTOCAD, and Solid Works, which are currently being used in industries, are equipped with tolerance features. The algorithms and programming codes that are in existence today are aimed at enhancing the accuracy with minimum material wastage. These programs have the capability of allotting tolerance ranges for different miniature parts of complex mechanical systems.



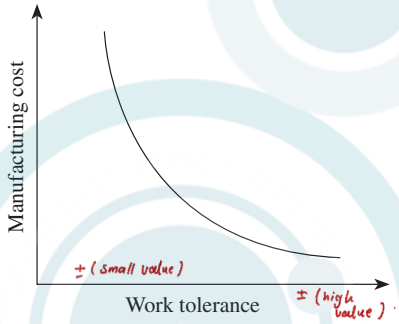
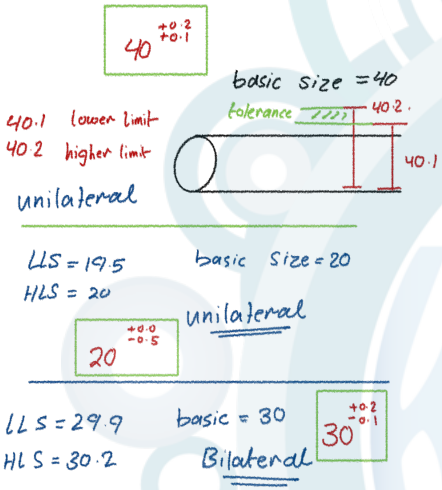


Fig. 3.2 Relationship between work tolerance and manufacturing cost

3.3.2 Manufacturing Cost and Work Tolerance

It is very pertinent to relate the production of components within the specified tolerance zone to its associated manufacturing cost. As the permissive tolerance goes on decreasing, the manufacturing cost incurred to achieve it goes on increasing exponentially. When the permissive tolerance limits are relaxed without degrading the functional requirements, the manufacturing cost decreases. This is clearly illustrated in Fig. 3.2.

Further, in order to maintain such close tolerance limits, manufacturing capabilities have to be enhanced, which certainly increases the manufacturing cost. The components manufactured have to undergo a closer scrutiny, which demands stringent inspection procedures and adequate instrumentation. This increases the cost of inspection. Hence, tolerance is a trade-off between the economical production and the accuracy required for proper functioning of the product. In fact, the tolerance limits specified for the components to be manufactured should be just sufficient to perform their intended functions.



3.3.3 Classification of Tolerance

Tolerance can be classified under the following categories:

1. Unilateral tolerance
2. Bilateral tolerance
3. Compound tolerance
4. Geometric tolerance

Ex: basic = 40
lower limit = 39.5
upper " = 39.8
diff. tolerance
Unilateral

Unilateral Tolerance

When the tolerance distribution is only on one side of the basic size, it is known as unilateral tolerance. In other words, tolerance limits lie wholly on one side of the basic size, either above or below it. This is illustrated in Fig. 3.3(a). Unilateral tolerance is employed when precision fits are required during assembly. This type of tolerance is usually indicated when the mating parts are also machined by the same operator. In this system, the total tolerance as related to the basic size is in one direction only. Unilateral tolerance is employed in the drilling process wherein dimensions of the hole are most likely to deviate in one direction only, that is, the hole is always oversized rather than undersized. This system is preferred because the basic size is used for the GO limit gauge. This helps in standardization of the GO gauge, as holes and shafts of different grades will have the same lower and upper limits, respectively. Changes in the magnitude of the tolerance affect only the size of the other gauge dimension, the NOT GO gauge size.

Example

$$40^{+0.02}_{+0.01},\ 40^{+0.02}_{-0.00},\ 40^{-0.01}_{-0.02},\ 40^{+0.00}_{-0.02}$$

Bilateral Tolerance

When the tolerance distribution lies on either side of the basic size, it is known as bilateral tolerance. In other words, the dimension of the part is allowed to vary on both sides of the basic

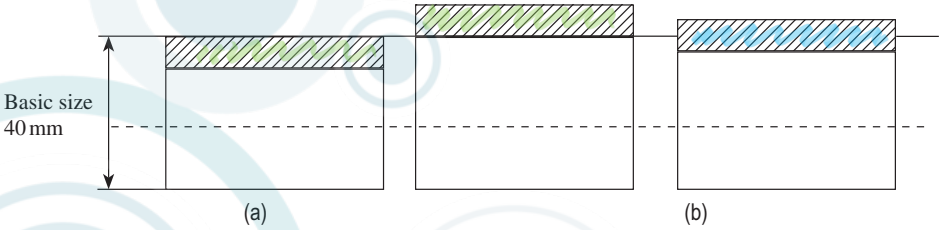


Fig. 3.3 Tolerances (a) Unilateral (b) Bilateral

size but may not be necessarily equally disposed about it. The operator can take full advantage of the limit system, especially in positioning a hole. This system is generally preferred in mass production where the machine is set for the basic size. This is depicted in Fig. 3.3(b). In case unilateral tolerance is specified in mass production, the basic size should be modified to suit bilateral tolerance.

Example

$40 \pm 0.02 \quad 40^{+0.02}_{-0.01}$

Compound Tolerance

When tolerance is determined by established tolerances on more than one dimension, it is known as compound tolerance For example, tolerance for the dimension *R* is determined by the combined effects of tolerance on 40 mm dimension, on 60º, and on 20 mm dimension. The tolerance obtained for dimension *R* is known as compound tolerance (Fig. 3.4). In practice, compound tolerance should be avoided as far as possible.

Geometric Tolerance

Normally, tolerances are specified to indicate the actual size or dimension of a feature such as a hole or a shaft. In order to manufacture components more accurately or with minimum dimensional variations, the manufacturing facilities and the labour required become more cost intensive. Hence, it is essential for the manufacturer to have an in-depth knowledge of tolerances, to manufacture quality and reliable components economically. In fact, depending on the application of the end product, precision is engineered selectively. Therefore, apart from considering the actual size, other geometric dimensions such as roundness and straightness of a shaft have to be considered while manufacturing components. The tolerances specified should also encompass such variations. However, it is difficult to combine all errors of roundness, straightness, and diameter within a single tolerance on diameter. Geometric tolerance is defined as the total amount that the dimension of a manufactured part can vary. Geometric tolerance underlines the importance of the shape of a feature as against its size. Geometric dimensioning and tolerancing is a method of defining parts based on how they function, using standard symbols. This method is frequently used in industries. Depending on the functional requirements, tolerance on

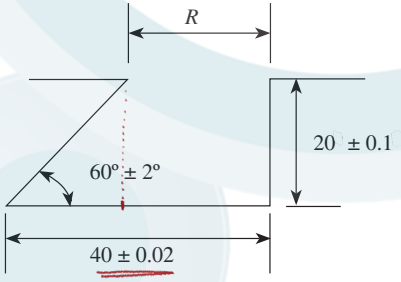


Fig. 3.4 Compound tolerance

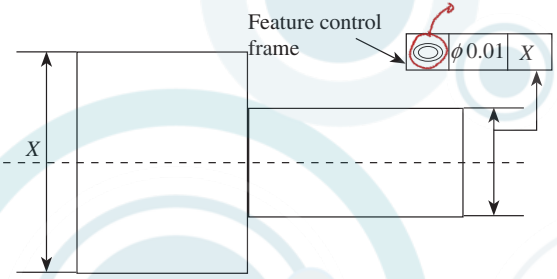


Fig. 3.5 Representation of geometric tolerance

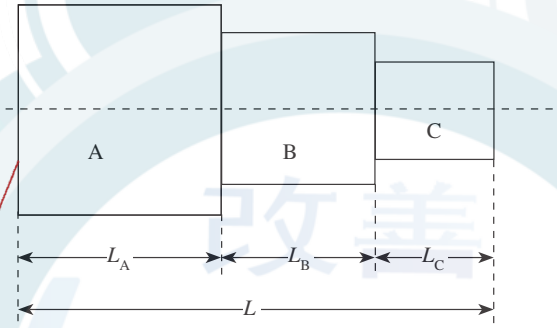


Fig. 3.6 Accumulation of tolerances

diameter, straightness, and roundness may be specified separately. Geometric tolerance can be classified as follows:

Form tolerances Form tolerances are a group of geometric tolerances applied to individual features. They limit the amount of error in the shape of a feature and are independent tolerances. Form tolerances as such do not require locating dimensions. These include straightness, circularity, flatness, and cylindricity.

Orientation tolerances Orientation tolerances are a type of geometric tolerances used to limit the direction or orientation of a feature in relation to other features. These are related tolerances. Perpendicularity, parallelism, and angularity fall into this category.

Positional tolerances Positional tolerances are a group of geometric tolerances that controls the extent of deviation of the location of a feature from its true position. This is a three-dimensional geometric tolerance comprising position, symmetry, and concentricity.

Geometric tolerances are used to indicate the relationship of one part of an object with another. Consider the example shown in Fig. 3.5. Both the smaller- and the larger-diameter cylinders need be concentric with each other. In order to obtain a proper fit between the two cylinders, both the centres have to be in line with each other. Further, perhaps both the cylinders are manufactured at different locations and need to be assembled on an interchangeable basis. It becomes imperative to indicate how much distance can be tolerated between the centres of these two cylinders. This information can be represented in the feature control frame that comprises three boxes. The first box on the left indicates the feature to be controlled, which is represented symbolically. In this example, it is concentricity. The box at the centre indicates the distance between the two cylinders that can be tolerated, that is, these two centres cannot be apart by more than 0.01 mm. The third box indicates that the datum is with X. The different types of geometric tolerances and their symbolic representation are given in Table 3.1.

Consider the example shown in Fig. 3.6.

Let $L_A = 30^{+0.02}_{-0.01}$ mm, $L_B = 20^{+0.02}_{-0.01}$ mm, and $L_C = 10^{+0.02}_{-0.01}$ mm.

The overall length of the assembly is the sum of the individual length of components given as

$$L = L_A + L_B + L_C$$
$$L = 30 + 20 + 10 = 60\,\text{mm}$$

Table 3.1 Symbolic representation of geometric tolerances

Type of geometric tolerance	Feature	Geometric characteristic	Definition	Symbol
Form tolerance	Independent	Straightness (two-dimensional)	Controls the extent of deviation of a feature from a straight line	
		Circularity (two-dimensional)	Exercises control on the extent of deviation of a feature from a perfect circle	
		Flatness (three-dimensional)	Controls the extent of deviation of a feature from a flat plane	
		Cylindricity (three-dimensional)	Controls the extent of deviation of a feature from a perfect cylinder	
	Related or single	Profile of a line (two-dimensional)	Controls the extent of deviation of an outline of a feature from the true profile	
		Profile of a surface (two-dimensional)	Exercises control on the extent of deviation of a surface from the true profile	
Orientation tolerance	Related	Perpendicularity (three-dimensional)	Exercises control on the extent of deviation of a surface, axis, or plane from a 90° angle	
		Parallelism (three-dimensional)	Controls the extent of deviation of a surface, axis, or plane from an orientation parallel to the specified datum	
		Angularity (three-dimensional)	Exercises controls on the deviation of a surface, axis, or plane from the angle described in the design specifications	
Position tolerance	Related	Position (three-dimensional)	Exercises control on the extent of deviation of location of a feature from its true position	
		Symmetry (three-dimensional)	Exercises control on extent of deviation of the median points between two features from a specified axis or centre plane	
		Concentricity (three-dimensional)	Exercises control on extent of deviation of the median points of multiple diameters from the specified datum axis	
Runout	Related	Circular runout (two-dimensional)	Exercises composite control on the form, orientation, and location of multiple cross-sections of a cylindrical part as it rotates	
		Total runout (three-dimensional)	Exercises simultaneous composite control on the form, orientation, and location of the entire length of a cylindrical part as it rotates	

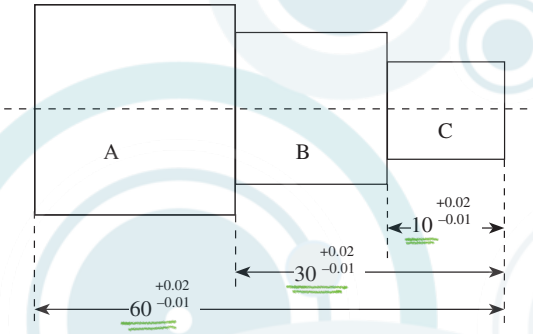


Fig. 3.7 Progressive dimensioning

Then, cumulative upper tolerance limit is 0.02 + 0.02 + 0.02 = 0.06 mm and cumulative lower limit = − 0.01 − 0.01 − 0.01 = −0.03 mm

Therefore, dimension of the assembled length will be = $60^{+0.06}_{-0.03}$ mm

It is essential to avoid or minimize the cumulative effect of tolerance build-up, as it leads to a high tolerance on overall length, which is undesirable. If progressive dimensioning from a common reference line or a baseline dimensioning is adopted, then tolerance accumulation effect can be minimized. This is clearly illustrated in Fig. 3.7.

3.4 MAXIMUM AND MINIMUM METAL CONDITIONS

Let us consider a shaft having a dimension of 40 ± 0.05 mm.

The maximum metal limit (MML) of the shaft will have a dimension of 40.05 mm because at this higher limit, the shaft will have the maximum possible amount of metal.

The shaft will have the least possible amount of metal at a lower limit of 39.95 mm, and this limit of the shaft is known as minimum or least metal limit (LML).

Similarly, consider a hole having a dimension of 45 ± 0.05 mm.

The hole will have a maximum possible amount of metal at a lower limit of 44.95 mm and the lower limit of the hole is designated as MML. For example, when a hole is drilled in a component, minimum amount of material is removed at the lower limit size of the hole. This lower limit of the hole is known as MML.

The higher limit of the hole will be the LML. At a high limit of 45.05 mm, the hole will have the least possible amount of metal. The maximum and minimum metal conditions are shown in Fig. 3.8.

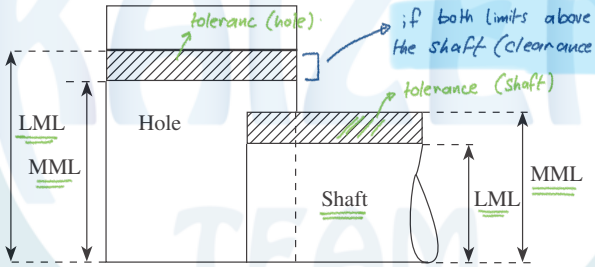


Fig. 3.8 MML and LML

3.5 FITS

Manufactured parts are required to mate with one another during assembly. The relationship between the two mating parts that are to be assembled, that is, the hole and the shaft, with respect to the difference in their dimensions before assembly is called a *fit*. An ideal fit is required for proper functioning of the mating parts. Three basic types of fits can be identified, depending on the actual limits of the hole or shaft:

1. Clearance fit

2. Interference fit
3. Transition fit

Clearance fit The largest permissible diameter of the shaft is smaller than the diameter of the smallest hole. This type of fit always provides clearance. Small clearances are provided for a precise fit that can easily be assembled without the assistance of tools. When relative motions are required, large clearances can be provided, for example, a shaft rotating in a bush. In case of clearance fit, the difference between the sizes is always positive. The clearance fit is described in Fig. 3.9.

Interference fit The minimum permissible diameter of the shaft exceeds the maximum allowable diameter of the hole. This type of fit always provides interference. Interference fit is a form of a tight fit. Tools are required for the precise assembly of two parts with an interference fit. When two mating parts are assembled with an interference fit, it will be an almost permanent assembly, that is, the parts will not come apart or move during use. To assemble the parts with interference, heating or cooling may be required. In an interference fit, the difference between the sizes is always negative. Interference fits are used when accurate location is of utmost importance and also where such location relative to another part is critical, for example, alignment of dowel pins. The interference fit is illustrated in Fig. 3.10.

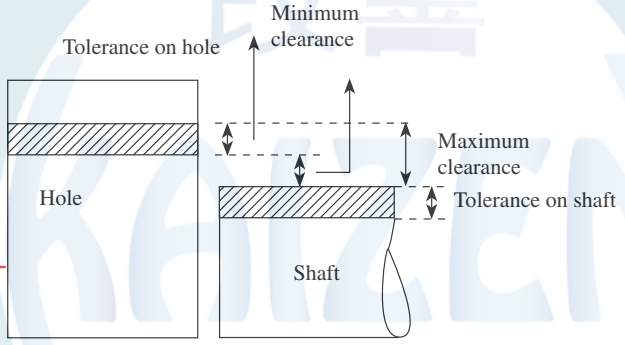


Fig. 3.9 Clearance fit

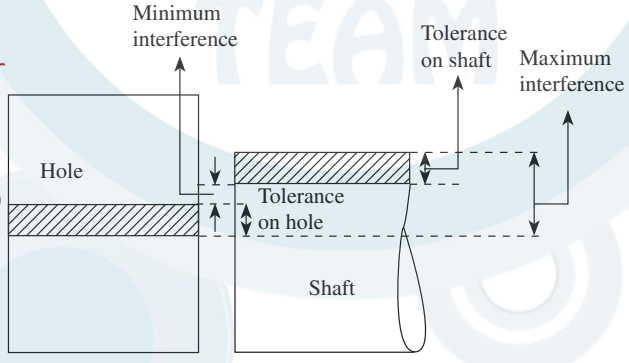


Fig. 3.10 Interference fit

Transition fit The diameter of the largest permissible hole is greater than the diameter of the smallest shaft and the diameter of the smallest hole is smaller than the diameter of the largest shaft. In other words, the combination of maximum diameter of the shaft and minimum diameter of the hole results in an interference fit, while that of minimum diameter of the shaft and maximum diameter of the hole yields a clearance fit. Since the tolerance zones overlap, this type of fit may sometimes provide clearance and sometimes interference, as depicted in Fig. 3.11. Precise assembly may be obtained with the assistance of tools, for example, dowel pins may be required in tooling to locate parts.

In a clearance fit, minimum clearance is the difference between minimum size of the hole, that is, low limit of the hole (LLH), and maximum size of the shaft, that is, high limit of the shaft (HLS), before assembly. In a transition or a

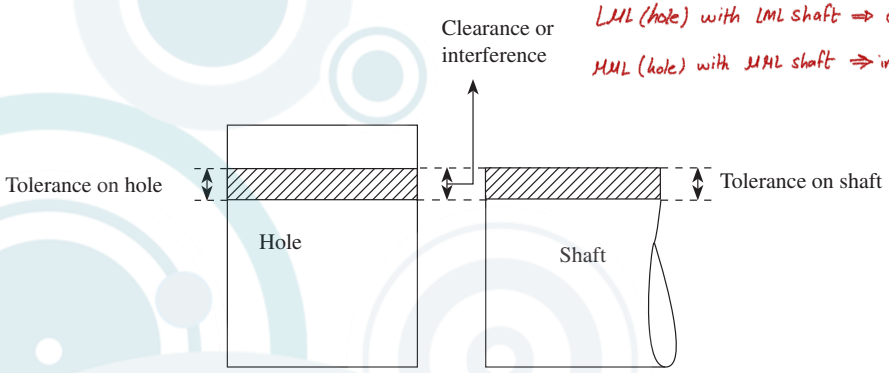


Fig. 3.11 Transition fit

clearance fit, maximum clearance is the arithmetical difference between the maximum size of the hole, that is, high limit of the hole (HLH), and the minimum size of the shaft, that is, low limit of the shaft (LLS), before assembly.

In an interference fit, minimum interference is the arithmetical difference between maximum size of the hole, that is, HLH, and minimum size of the shaft, that is, LLS, before assembly. In a transition or an interference fit, it is the arithmetical difference between minimum size of the hole, that is, LLH, and maximum size of the shaft, that is, HLS, before assembly.

Thus, in order to find out the type of fit, one needs to determine HLH – LLS and LLH – HLS. If both the differences are positive, the fit obtained is a clearance fit, and if negative, it is an interference fit. If one difference is positive and the other is negative, then it is a transition fit.

The three basic types of fits, clearance, transition, and interference, can be further classified, as shown in Fig. 3.12.

3.5.1 Allowance

An allowance is the intentional difference between the maximum material limits, that is, LLH and HLS (minimum clearance or maximum interference) of the two mating parts. It is the

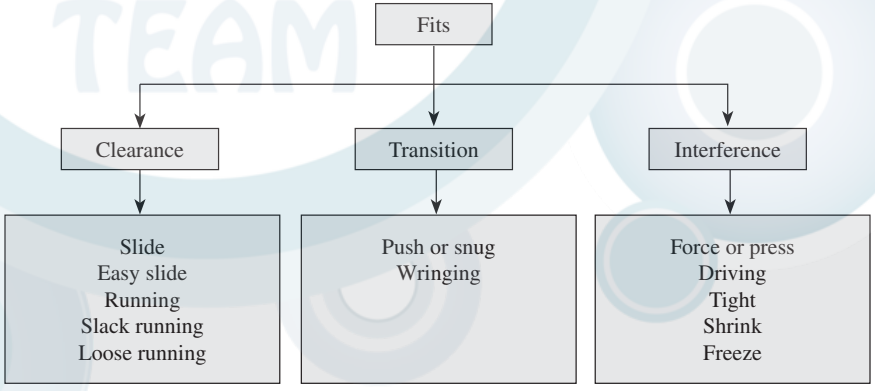


Fig. 3.12 Detailed classification of fits

Table 3.2 Examples of different types of fits

Description of fit	Class of fit	Application area
	Clearance fit	
Slide	H7/h6	Sealing rings, bearing covers, movable gears in change gear trains, clutches, etc.
Easy slide	H7/g7	Lathe spindle, spigots, piston, and slide valves
Running	H8/f8	Lubricated bearings (with oil or grease), pumps and smaller motors, gear boxes, shaft pulleys, etc.
Slack running	H8/c11	Oil seals with metal housings, multi-spline shafts, etc.
Loose running	H8/d9	Loose pulleys, loose bearings with low revolution, etc.
	Interference fit	
Force or press	H8/r6	Crankpins, car wheel axles, bearing bushes in castings, etc.
Driving	H7/s6	Plug or shaft slightly larger than the hole
Tight	H7/p6	Stepped pulleys on the drive shaft of a conveyor
Shrink	H7/u6, H8/u7	Bronze crowns on worm wheel hubs, couplings, gear wheels, and assembly of piston pin in IC engine piston
Freeze	H7/u6, H8/u7	Insertion of exhaust valve seat inserts in engine cylinder blocks and insertion of brass bushes in various assemblies
	Transition fit	
Push or snug	H7/k6	Pulleys and inner ring of ball bearings on shafts
Wringing	H7/n6	Gears of machine tools

prescribed difference between the dimensions of the mating parts to obtain the desired type of fit. Allowance may be positive or negative. Positive allowance indicates a clearance fit, and an interference fit is indicated by a negative allowance.

Allowance = LLH – HLS

Table 3.2 gives examples of the classification of fits.

3.5.2 Hole Basis and Shaft Basis Systems

To obtain the desired class of fits, either the size of the hole or the size of the shaft must vary. Two types of systems are used to represent the three basic types of fits, namely clearance, interference, and transition fits. They are (a) hole basis system and (b) shaft basis system.

Although both systems are the same, hole basis system is generally preferred in view of the functional properties.

Hole Basis System

In this system, the size of the hole is kept constant and the shaft size is varied to give various types of fits. In a hole basis system, the fundamental deviation or lower deviation of the hole is zero, that is, the lower limit of the hole is the same as the basic size. The two limits of the shaft and the higher dimension of the hole are then varied to obtain the desired type of fit, as illustrated in Fig. 3.13.

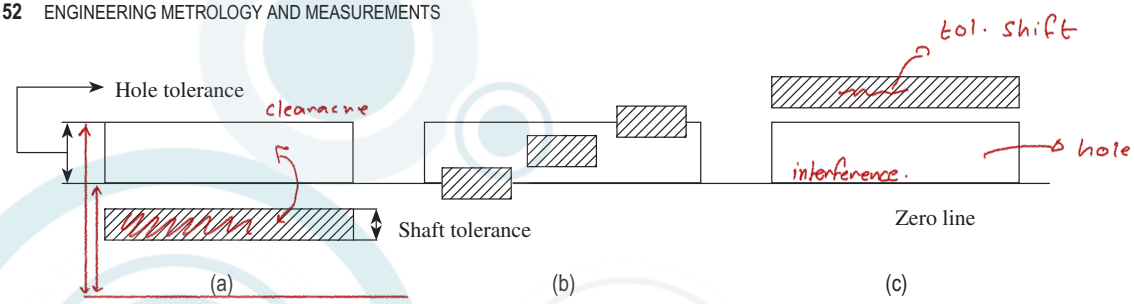


Fig. 3.13 Hole basis system (a) Clearance fit (b) Transition fit (c) Interference fit

This type of system is widely adopted in industries, as it is easier to manufacture shafts of varying sizes to the required tolerances. Standard size drills or reamers can be used to obtain a variety of fits by varying only the shaft limits, which leads to greater economy of production. The shaft can be accurately produced to the required size by standard manufacturing processes, and standard-size plug gauges are used to check hole sizes accurately and conveniently.

Shaft Basis System

The system in which the dimension of the shaft is kept constant and the hole size is varied to obtain various types of fits is referred to as shaft basis system. In this system, the fundamental deviation or the upper deviation of the shaft is zero, that is, the HLH equals the basic size. The desired class of fits is obtained by varying the lower limit of the shaft and both limits of the hole, as shown in Fig. 3.14.

This system is not preferred in industries, as it requires more number of standard-size tools such as reamers, broaches, and gauges, which increases manufacturing and inspection costs. It is normally preferred where the hole dimension is dependent on the shaft dimension and is used in situations where the standard shaft determines the dimensions of the mating parts such as couplings, bearings, collars, gears, and bushings.

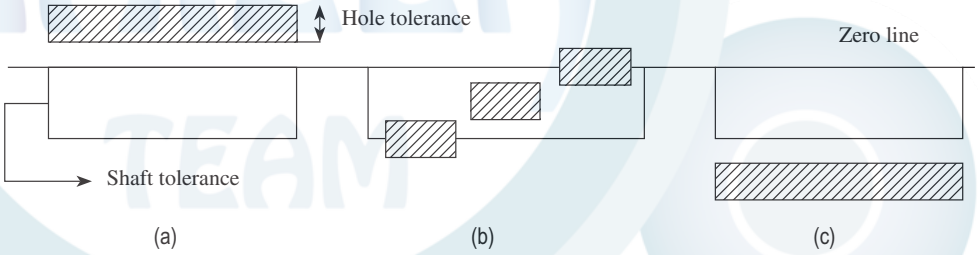


Fig. 3.14 Shaft basis system (a) Clearance fit (b) Transition fit (c) Interference fit

3.5.3 Numerical Examples

Example 3.1 In a limit system, the following limits are specified for a hole and shaft assembly:

Hole = $30^{+0.02}_{+0.00}$ mm and shaft = $30^{-0.02}_{-0.05}$ mm

Determine the (a) tolerance and (b) allowance.

Solution

(a) Determination of tolerance:

Tolerance on hole = HLH − LLH
= 30.02 − 30.00 = 0.02 mm

Tolerance on shaft = HLS − LLS
= [(30 − 0.02) − (30 − 0.05)] = 0.03 mm

(b) Determination of allowance:

Allowance = Maximum metal condition of hole − Maximum metal condition of shaft
= LLH − HLS
= 30.02 − 29.98 = 0.04 mm

Example 3.2 The following limits are specified in a limit system, to give a clearance fit between a hole and a shaft:

Hole = $25^{+0.03}_{-0.00}$ mm and shaft = $25^{-0.006}_{-0.020}$ mm

Determine the following:
(a) Basic size
(b) Tolerances on shaft and hole
(c) Maximum and minimum clearances

Solution

(a) Basic size is the same for both shaft and hole.

(b) Determination of tolerance:

Tolerance on hole = HLH − LLH
= 25.03 − 25.00 = 0.03 mm

Tolerance on shaft = HLS − LLS
= [(25 − 0.006) − (25 − 0.020)] = 0.014 mm

Determination of clearances:

Maximum clearance = HLH − LLS
= 25.03 − 24.98 = 0.05 mm

Minimum clearance = LLH − HLS
= 25.00 − (25 − 0.006) = 0.06 mm

Example 3.3 Tolerances for a hole and shaft assembly having a nominal size of 50 mm are as follows:

Hole = $50^{+0.02}_{+0.00}$ mm and shaft = $50^{-0.05}_{-0.08}$ mm

Determine the following:
(a) Maximum and minimum clearances
(b) Tolerances on shaft and hole
(c) Allowance
(d) MML of hole and shaft
(e) Type of fit

Solution

(a) Determination of clearances:

Maximum clearance = HLH − LLS
= 50.02 − (50 − 0.08) = 0.10 mm

Minimum clearance = LLH − HLS
= 50.00 − (50 − 0.005) = 0.05 mm

(b) Determination of tolerance:

Tolerance on hole = HLH − LLH
= 50.02 − 50.00 = 0.02 mm

Tolerance on shaft = HLS − LLS
= [(50 − 0.05) − (50 − 0.08)] = 0.03 mm

(c) Determination of allowance:

Allowance = Maximum metal condition of hole − Maximum metal condition of shaft
= LLH − HLS
= 50.00 − (50 − 0.05) = 0.05 mm

(d) Determination of MMLs:

MML of hole = Lower limit of hole = 50.00 mm

MML of shaft = Higher limit of shaft = 50.00 − 0.05 = 49.05 mm

(e) Since both maximum and minimum clearances are positive, it can be conclude that the given pair has a clearance fit.

Example 3.4 A clearance fit has to be provided for a shaft and bearing assembly having a diameter of 40 mm. Tolerances on hole and shaft are 0.006 and 0.004 mm, respectively. The tolerances are disposed unilaterally. If an allowance of 0.002 mm is provided, find the limits of size for hole and shaft when (a) hole basis system and (b) shaft basis system are used.

Solution

(a) When hole basis system is used:

Hole size:

HLH = 40.006 mm

LLH = 40.000 mm

The allowance provided is +0.002 mm.

Therefore, HLS = LLH − Allowance
= 40.000 − 0.002 = 39.998 mm

LLS = HLS − Tolerance
= 39.998 − 0.004 = 39.994 mm

(b) When shaft basis system is used:

Shaft size:

HLS = 40.000 mm

LLS = 40.000 − 0.004 = 39.996 mm

The allowance provided is +0.002 mm.

Therefore, LLH = HLS + allowance
= 40.000 + 0.002 = 40.002 mm

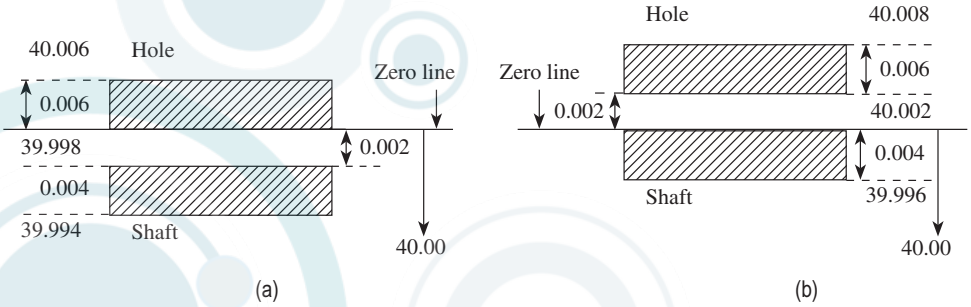


Fig. 3.15 Disposition of tolerances (a) Hole basis system (b) Shaft basis system

HLH = 40.002 + 0.006 = 40.008 mm

The disposition of tolerance for both hole basis and shaft basis systems are given in Fig. 3.15.

Example 3.5 For the following hole and shaft assembly, determine (a) hole and shaft tolerance and (b) type of fit.

Hole = $20^{+0.025}_{+0.000}$ mm and shaft = $20^{+0.080}_{+0.005}$ mm

Solution

(a) Determination of tolerance:

Tolerance on hole = HLH − LLH
= 20.025 − 20.00 = 0.025 mm

Tolerance on shaft = HLS − LLS
= 20.080 − 20.005 = 0.075 mm

(b) To determine the type of fit, calculate maximum and minimum clearances:

Maximum clearance = HLH − LLS
= 20.025 − 20.005 = 0.020 mm

(Clearance because the difference is positive)

Minimum clearance = LLH − HLS
= 20.00 − 20.080 = −0.08 mm

(Interference because the difference is negative)

Since one difference is positive and the other negative, it can be concluded that the given hole and shaft pair has a transition fit.

Example 3.6 For the following hole and shaft assembly, determine (a) hole and shaft tolerance and (b) type of fit

Hole = $20^{+0.05}_{+0.00}$ mm and shaft = $20^{+0.08}_{+0.06}$ mm

Solution

(a) Determination of tolerance:

Tolerance on hole = HLH – LLH
= 20.05 – 20.00 = 0.05 mm
Tolerance on shaft = HLS – LLS
= 20.08 – 20.06 = 0.02 mm

(b) To determine the type of fit, calculate maximum and minimum clearances:
Maximum clearance = HLH – LLS
= 20.05 – 20.06 = –0.01 mm
Minimum clearance = LLH – HLS
= 20.00 – 20.08 = –0.08 mm

Since both differences are negative, it can be concluded that the given hole and shaft pair has an interference fit.

3.6 SYSTEM OF LIMITS AND FITS

The rapid growth of national and international trade necessitates the developments of formal systems of limits and fits, at the national and international levels. Economic success of most manufacturing industries critically depends on the conformity of the specifications of the products to international standards. The International Organization for Standardization (ISO) specifies the internationally accepted system of limits and fits. Indian standards are in accordance with the ISO.

The ISO system of limits and fits comprises 18 grades of fundamental tolerances to indicate the level of accuracy of the manufacture. These fundamental tolerances are designated by the letters IT followed by a number. The ISO system provides tolerance grades from IT01, IT0, and IT1 to IT16 to realize the required accuracy. The greater the number, the higher the tolerance limit. The choice of tolerance is guided by the functional requirements of the product and economy of manufacture. The degree of accuracy attained depends on the type and condition of the machine tool used. Table 3.3 gives the fundamental tolerance values required for various applications.

Tolerance values corresponding to grades IT5–IT16 are determined using the standard tolerance unit (i, in μm), which is a function of basic size.

Tolerance = Max. dia – min. dia.
= $E_s - E_i$
= $e_s - e_i$

Table 3.3 Tolerances grades for different applications

Fundamental tolerance	Applications
IT01–IT4	For production of gauges, plug gauges, and measuring instruments
IT5–IT7	For fits in precision engineering applications such as ball bearings, grinding, fine boring, high-quality turning, and broaching
IT8–IT11	For general engineering, namely turning, boring, milling, planning, rolling, extrusion, drilling, and precision tube drawing
IT12–IT14	For sheet metal working or press working
IT15–IT16	For processes such as casting, stamping, rubber moulding, general cutting work, and flame cutting

$$i = 0.453\sqrt[3]{D} + 0.001D \text{ microns}$$

where D is the diameter of the part in mm. The linear factor $0.001D$ counteracts the effect of measuring inaccuracies that increase by increasing the measuring diameter. By using this formula, the value of tolerance unit 'i' is obtained for sizes up to 500 mm. D is the geometric mean of the lower and upper diameters of a particular diameter step within which the given or chosen diameter D lies and is calculated by using the following equation:

$$\sqrt{D_{max} \times D_{min}}$$

The various steps specified for the diameter steps are as follows:

1–3, 3–6, 6–10, 10–18, 18–30, 30–50, 50–80, 80–120, 120–180, 180–250, 250–315, 315–400, 400–500 500–630, 630–800, and 800–1000 mm.

Tolerances have a parabolic relationship with the size of the products. The tolerance within which a part can be manufactured also increases as the size increases. The standard tolerances corresponding to IT01, IT0, and IT1 are calculated using the following formulae:

IT01: $0.3 + 0.008D$
IT0: $0.5 + 0.012D$
IT1: $0.8 + 0.020D$

The values of tolerance grades IT2–IT4, which are placed between the tolerance grades of IT1 and IT5, follow a geometric progression to allow for the expansion and deformation affecting both the gauges and the workpieces as dimensions increase. For the tolerance grades IT6–IT16, each grade increases by about 60% from the previous one, as indicated in Table 3.4.

Table 3.4 Standard tolerance units

Tolerance grade	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16
Standard tolerance unit (i)	10	16	25	40	64	100	160	250	400	640	1000

The tolerance zone is governed by two limits: the size of the component and its position related to the basic size. The position of the tolerance zone, from the zero line (basic size), is determined by fundamental deviation. The ISO system defines 28 classes of basic deviations for holes and shafts, which are marked by capital letters A, B, C, ..., ZC (with the exception of I, L, O, Q, and W) and small letters a, b, c, ..., zc (with the exception of i, l, o, q, and w), respectively, as depicted in Fig. 3.16. Different combinations of fundamental deviations and fundamental tolerances are used to obtain various types of fits.

The values of these tolerance grades or fundamental deviations depend on the basic size of the assembly. The different values of standard tolerances and fundamental deviations can be obtained by referring to the design handbook. The choice of the tolerance grade is governed by the type of manufacturing process and the cost associated with it. From Fig. 3.16, a typical case can be observed in which the fundamental deviation for both hole H and shaft h having a unilateral tolerance of a specified IT grade is zero. The first eight designations from A (a) to H (h) for holes (shafts) are intended to be used in clearance fit, whereas the remaining designations, JS (js) to ZC (zc) for holes (shafts), are used in interference or transition fits. For JS, the two deviations are equal and given by ±IT/2.

Consider the designation 40 H7/d9. In this example, the basic size of the hole and shaft is 40 mm. The nature of fit for the hole basis system is designated by H and the fundamental deviation of the hole is zero. The tolerance grade is indicated by IT7. The shaft has a d-type fit for which the fundamental deviation (upper deviation) has a negative value, that is, its dimension falls below the basic size having IT9 tolerance.

Depending on the application, numerous fits ranging from extreme clearance to extreme interference can be selected using a suitable combination of fundamental deviations and fundamental tolerances. From Fig. 3.16, it can be seen that the lower deviation for the holes 'A' to 'G' is above the zero line and that for 'K' to 'ZC' is below the zero line. In addition, it can be observed that for shafts 'a' to 'g', the upper deviation falls below the zero line, and for 'k' to 'zc' it is above the zero line.

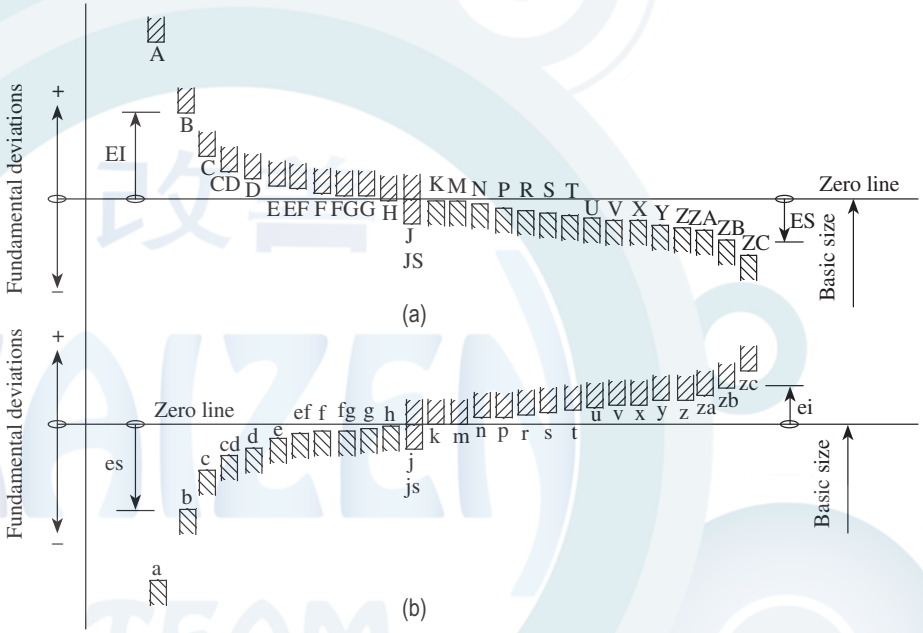


Fig. 3.16 Typical representation of different types of fundamental deviations
(a) Holes (internal features) (b) Shafts (external features)

It can be seen from Fig. 3.17 that 'EI' is above the zero line for holes 'A' to 'G', indicating positive fundamental deviation. In contrast, Fig. 3.18 shows that 'ei' is below the zero line for the shafts 'a' to 'g' and therefore the fundamental deviation is negative. In addition, from Figs 3.17 and 3.18, it can be observed that for holes 'K' to 'ZC', the fundamental deviation is negative ('EI' below the zero line), whereas for shafts 'k' to 'zc', it is positive ('ei' above the zero line).

It follows from Figs 3.17 and 3.18 that the values of 'ES' and 'EI' for the holes and 'es' and 'ei' for the shafts can be determined by adding and subtracting the fundamental tolerances, respectively. Magnitude and sign of fundamental deviations for the shafts, either upper deviation 'es' or lower deviation 'ei' for each symbol, can be determined

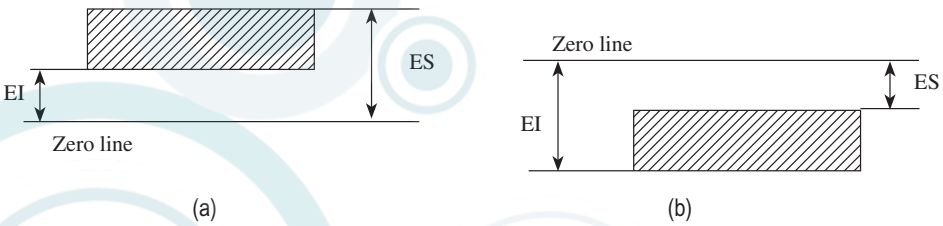


Fig. 3.17 Deviations for holes (a) Deviations for A to G (b) Deviations for K to Z_i

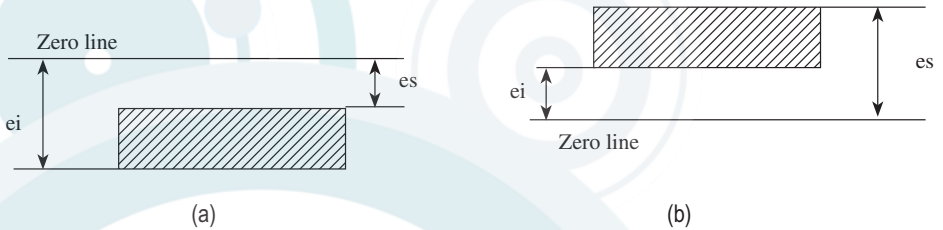


Fig. 3.18 Deviations for shafts (a) Deviations for a to g (b) Deviations for k to Z_i

from the empirical relationships listed in Tables 3.5 and 3.6, except for shafts j and js for which there is no fundamental deviation. The values given in Tables 3.5 and 3.6 are as per IS: 919. The

Table 3.5 Fundamental deviation formulae for shafts of sizes up to 500 mm

Upper deviation (es)		Lower deviation (ei)	
Shaft designation	In μm (for D in mm)	Shaft designation	In μm (for D in mm)
a	$= -(265 + 1.3D)$ for $D \le 120$ $= -3.5D$ for $D > 120$	j5–j8	No formula
		(For js two deviations are equal to IT ± 2)	
		k4–k7	$= +0.6\sqrt[3]{D}$
		For grades ≤k3 to ≥k8	= 0
b	$= -(140 + 0.85D)$ for $D \le 160$ $= -1.8D$ for $D > 160$	m	$= +$(IT7 − IT6)
		n	$= +5D^{0.34}$
		p	= ± IT7 + 0 to 5
c	$= -52D^{0.2}$ for D + IT7 + 0 to 40 $= -(95 + 0.8D)$ for $D > 40$	r	= Geometric mean of ei values for p and s
			= +IT8 + 1 to 4 for $D \le 50$
d	$= -16D^{0.44}$	s	= +IT7 + 0.4D for $D > 50$
e	$= -11D^{0.41}$	t	= +IT7 + 0.63D
f	$= -5.5D^{0.41}$	u	= +IT7 + D
g	$= -2.5D^{0.34}$	v	= +IT7 + 1.25D

(Contd)

Table 3.5 (Contd)

h	= 0	x	= +IT7 + 1.6*D*
		y	= +IT7 + 2*D*
		z	= +IT7 + 2.5*D*
		za	= +IT8 + 3.15*D*
		zb	= +IT9 + 4*D*
		zc	= +IT10 + 5*D*

Table 3.6 Fundamental deviation formulae for holes of sizes up to 500 mm

For all deviations except the following:			General rule: Hole limits are identical with the shaft limits of the same symbol (letter and grade) but disposed on the other side of the zero line EI = upper deviation es of shaft of the same letter symbol but of opposite sign
For sizes above 3 mm	N	9 and coarser grades	ES = 0
	J, K, M, and N	Up to grade 8 inclusive	Special rule: ES = lower deviation ei of the shaft of the same letter symbol but one grade finer and of opposite sign, increased by the difference between the tolerances of the two grades in question
	P to ZC	Up to grade 7 inclusive	

other deviations of the holes and shafts can be determined using the following relationships that can be derived from Figs 3.17 and 3.18:

1. For holes A to G, EI is a positive fundamental deviation and EI = ES − IT.
2. For holes K to Z*i*, the fundamental deviation ES is negative and ES = EI − IT.
3. For shafts 'a' to 'g', the fundamental deviation es is negative and es = ei − IT.
4. For shafts 'k' to 'Z*i*', the fundamental deviation ei is positive, and ei = es − IT.

Production of large-sized components is associated with problems pertaining to manufacture and measurement, which do not exist in the case of smaller-sized components. As the size of the components to be manufactured increases, the difficulty in making accurate measurements also increases. Variations in temperature also affect the quality of measurement.

When the size of the components to be manufactured exceeds 500 mm, the tolerance grades IT01–IT5 are not provided, as they are considered to be too small. The fundamental tolerance unit in case of sizes exceeding 500 and up to 3150 mm is determined as follows:

$i = 0.004D + 2.1D$, where D is 0.001 mm.

The fundamental deviations for holes and shafts are given in Table 3.7, which are as per IS: 2101.

Table 3.7 Fundamental deviation for shafts and holes of sizes from above 500 to 3150 mm

Shafts			Holes			Formula for deviations in μm
Type	Fundamental deviation	Sign	Type	Fundamental deviation	Sign	(for D in mm)
d	es	−	D	EI	+	$16D^{0.44}$
e	es	−	E	EI	+	$11D^{0.41}$
f	es	−	F	EI	+	$5.5D^{0.41}$
g	es	−	G	EI	+	$2.5D^{0.34}$
h	es	No sign	H	EI	No sign	0
js	ei	−	JS	ES	+	0.5ITπ
k	ei	−	K	ES	−	0
m	ei	+	M	ES	−	$0.024D + 12.6$
n	ei	+	N	ES	−	$0.04D + 21$
P	ei	+	P	ES	−	$0.072D + 37.8$
r	ei	+	R	ES	−	Geometric mean of the values for p and s or P and S
s	ei	+	S	ES	−	IT7 + $0.4D$
t	ei	+	T	ES	−	IT7 + $0.63D$
u	ei	+	U	ES	−	IT7 + D

في شكل ملف شيع المرفوعة الماضية

3.6.1 General Terminology

The following are the commonly used terms in the system of limits and fits.

Basic size This is the size in relation to which all limits of size are derived. Basic or nominal size is defined as the size based on which the dimensional deviations are given. This is, in general, the same for both components.

Limits of size These are the maximum and minimum permissible sizes acceptable for a specific dimension. The operator is expected to manufacture the component within these limits. The maximum limit of size is the greater of the two limits of size, whereas the minimum limit of size is the smaller of the two.

Tolerance This is the total permissible variation in the size of a dimension, that is, the difference between the maximum and minimum limits of size. It is always positive.

Allowance It is the intentional difference between the LLH and HLS. An allowance may be either positive or negative.

Allowance = LLH − HLS

Grade This is an indication of the tolerance magnitude; the lower the grade, the finer the tolerance.

Deviation It is the algebraic difference between a size and its corresponding basic size. It may be positive, negative, or zero.

Upper deviation It is the algebraic difference between the maximum limit of size and its corresponding basic size. This is designated as 'ES' for a hole and as 'es' for a shaft.

Lower deviation It is the algebraic difference between the minimum limit of size and its corresponding basic size. This is designated as 'EI' for a hole and as 'ei' for a shaft.

Actual deviation It is the algebraic difference between the actual size and its corresponding basic size.

Fundamental deviation It is the *minimum* difference between the size of a component and its basic size. This is identical to the upper deviation for shafts and lower deviation for holes. It is the closest deviation to the basic size. The fundamental deviation for holes are designated by capital letters, that is, A, B, C, …, H, …, ZC, whereas those for shafts are designated by small letters, that is, a, b, c…, h…, zc. The relationship between fundamental, upper, and lower deviations is schematically represented in Fig. 3.19.

Zero line This line is also known as the line of zero deviation. The convention is to draw the zero line horizontally with positive deviations represented above and negative deviations indicated below. The zero line represents the basic size in the graphical representation.

Shaft and hole These terms are used to designate all the external and internal features of any shape and not necessarily cylindrical.

Fit It is the relationship that exists between two mating parts, a hole and a shaft, with respect to their dimensional difference before assembly.

Maximum metal condition This is the maximum limit of an external feature; for example, a shaft manufactured to its high limits will contain the maximum amount of metal. It is also the minimum limit of an internal feature; for example, a component that has a hole bored in it to its lower limit of size will have the minimum amount of metal removed and remain in its

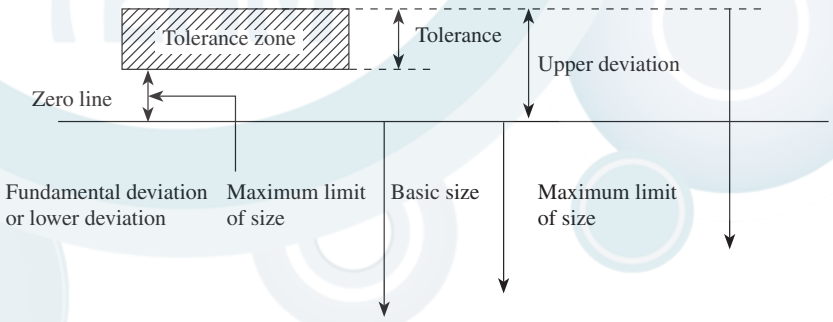


Fig. 3.19 Relationship between fundamental, upper, and lower deviations

maximum metal condition, (i.e., this condition corresponds to either the largest shaft or the smallest hole). This is also referred to as the GO limit.

Least metal condition This is the minimum limit of an external feature; for example, a shaft will contain minimum amount of material, when manufactured to its low limits. It is also the maximum limit of an internal feature; for example, a component will have the maximum amount of metal removed when a hole is bored in it to its higher limit of size, this condition corresponds to either the smallest shaft or the largest hole. This is also referred to as the NO GO limit.

Tolerance zone The tolerance that is bound by the two limits of size of the component is called the tolerance zone. It refers to the relationship of tolerance to basic size.

International tolerance grade (IT) Tolerance grades are an indication of the degree of accuracy of the manufacture. Standard tolerance grades are designated by the letter IT followed by a number, for example, IT7. These are a set of tolerances that varies according to the basic size and provides a uniform level of accuracy within the grade.

Tolerance class It is designated by the letter(s) representing the fundamental deviation followed by the number representing the standard tolerance grade. When the tolerance grade is associated with letter(s) representing a fundamental deviation to form a tolerance class, the letters IT are omitted and the class is represented as H8, f7, etc.

Tolerance symbols These are used to specify the tolerance and fits for mating components. For example, in 40 H8f7, the number 40 indicates the basic size in millimetres; capital letter H indicates the fundamental deviation for the hole; and lower-case letter f indicates the shaft. The numbers following the letters indicate corresponding IT grades.

3.6.2 Limit Gauging

Eli Whitney, who is hailed as the father of the American system, won the first contract in 1798 for the production of muskets and developed the gauging system. Richard Roberts of the United Kingdom first used plug and collar gauges for dimensional control. In 1857, Joseph Whitworth demonstrated internal and external gauges for use with a shaft-based limit system.

As discussed in Section 3.1, in mass production, components are manufactured in accordance with the permissive tolerance limits, as suggested by the designer. Production of components within the permissive tolerance limits facilitates interchangeable manufacture. It is also essential to check whether the dimensions of the manufactured components are in accordance with the specifications or not. Therefore, it is required to control the dimensions of the components. Several methods are available to achieve the control on dimensions. Various precision measuring instruments can be used to measure the actual dimensions of the components, which can be compared with the standard specified dimensions to decide the acceptability of these components.

In mass production, where a large number of similar components are manufactured on an interchangeable basis, measuring the dimensions of each part will be a time-consuming and expensive exercise. In addition, the actual or absolute size of a component, provided that it is within the limits specified, is not of much importance because the permissible limits of

variations in dimensions would have been specified by the designer in a logical manner, giving due consideration to the functional requirements. Therefore, in mass production, gauges can be used to check for the compliance of the limits of the part with the permissive tolerance limits, instead of measuring the actual dimensions. The term 'limit gauging' signifies the use of gauges for checking the limits of the components. Gauging plays an important role in the control of dimensions and interchangeable manufacture.

Limit gauges ensure that the components lie within the permissible limits, but they do not determine the actual size or dimensions. Gauges are scaleless inspection tools, which are used to check the conformance of the parts along with their forms and relative positions of the surfaces of the parts to the limits. The gauges required to check the dimensions of the components correspond to two sizes conforming to the maximum and minimum limits of the components. They are called GO gauges or NO GO or NOT GO gauges, which correspond, respectively, to the MML and LML of the component, as depicted in Figs 3.20 and 3.21. As discussed in section 3.4, MML is the lower limit of a hole and higher limit of the shaft and LML corresponds to the higher limit of a hole and lower limit of the shaft. The GO gauge manufactured to the maximum limit will assemble with the mating (opposed) part, whereas the NOT GO gauge corresponding to the low limit will not, hence the names GO and NOT GO gauges, respectively.

Practically, every gauge is a replica of the part that mates with the part for which the gauge has been designed. Consider an example of the manufacture of a cylinder that mates with a piston. The plug gauge, using which the cylinder bore is checked, is a copy of the opposed part (piston) as far as its form and size are concerned. When a gauge is designed as a replica

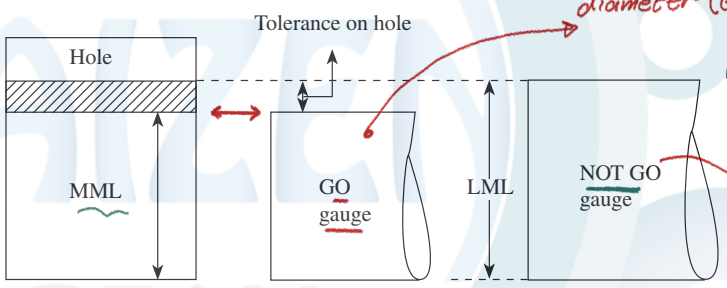


Fig. 3.20 Metal limits for hole gauging

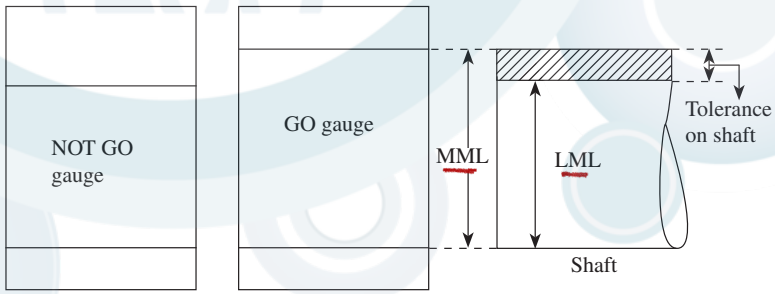


Fig. 3.21 Metal limits for shaft gauging

of the mating (opposed) part so far as the dimension to be checked is concerned, it is known as 'standard gauge'. The main intention in the design of gauges is simplicity, which helps in making continuous and accurate measurements.

It is important to note that normally clearance fits are preferred for a majority of the assembly operations. Allowance or minimum clearance is determined by the algebraic difference of the MMLs of the mating parts. Therefore, for clearance fits, the MMLs of the mating parts become more critical than the LMLs. This assumes importance for the following two reasons:

1. MMLs are crucial for effective functioning of the parts.
2. If the MMLs slightly exceed the specified values then assembly itself becomes impossible.

As discussed earlier, for gauging the MMLs of the mating parts, GO gauges are used. Therefore, it becomes imperative that special attention needs to be given when GO gauges are designed for gauging these limits. Whenever the components are gauged for their MMLs, if the GO gauges fail to assemble during inspection, the components should not be accepted under any circumstances. The minimum limits in a clearance fit of a product are not so critical because even if they exceed the specified limits and the NOT GO gauge assembles, its acceptance may result in functional degradation and because of the reduced quality the useful life of the product may get affected. Hence, it becomes essential that more care is taken especially when GO gauges are used, when compared to NOT GO gauges during inspection.

3.6.3 Classification of Gauges

The detailed classification of the gauges is as follows:

1. Plain gauges

(a) According to their type:
- (i) Standard gauges
- (ii) Limit gauges

(b) According to their purpose:
- (i) Workshop
- (ii) Inspection
- (iii) Reference, or master, or control gauges

(c) According to the form of the tested surface:
- (i) Plug gauges for checking holes
- (ii) Snap and ring gauges for checking shafts

(d) According to their design:
- (i) Single- and double-limit gauges
- (ii) Single- and double-ended gauges
- (iii) Fixed and adjustable gauges

2. Adjustable-type gap gauges
3. Miscellaneous gauges
   - (a) Combined-limit gauges
   - (b) Taper gauges
   - (c) Position gauges
   - (d) Receiver gauges

ideal case :
– assuming there is no tolerance to (GO/NOT GO)

(e) Contour gauges
(f) Profile gauges

3.6.4 Taylor's Principle

In 1905, William Taylor developed a concept relating to the gauging of components, which has been widely used since then. Since World War II, the term Taylor's principle has generally been applied to the principle of limit gauging and extensively used in the design of limit gauges. Prior to 1905, simple GO gauges were used. The components were carefully manufactured to fit the gauges. Since NOT GO gauges were not used, these components were without tolerance on their dimensions.

The theory proposed by Taylor, which is extensively used in the design of limit gauges, not only defines the function, but also defines the form of most limit gauges.

Taylor's principle states that the GO gauge is designed to check maximum metal conditions, that is, LLH and HLS. It should also simultaneously check as many related dimensions, such as roundness, size, and location, as possible.

The NOT GO gauge is designed to check minimum metal conditions, that is, HLH and LLS. It should check only one dimension at a time. Thus, a separate NOT GO gauge is required for each individual dimension.

During inspection, the GO side of the gauge should enter the hole or just pass over the shaft under the weight of the gauge without using undue force. The NOT GO side should not enter or pass.

The basic or nominal size of the GO side of the gauge conforms to the LLH or HLS, since it is designed to check maximum metal conditions. In contrast, the basic or nominal size of the NOT GO gauge corresponds to HLH or LLS, as it is designed to check minimum metal conditions.

It can be seen from Fig. 3.22 that the size of the GO plug gauge corresponds to the LLH and the NOT GO plug gauge to the HLH. Conversely, it can be observed from Fig. 3.23 that the GO snap gauge represents the HLS, whereas the NOT GO snap gauge represents the LLS.

It is pertinent to discuss here that since the GO plug is used to check more than one dimension of the hole simultaneously, the GO plug gauge must have a full circular section and must be of full length of the hole so that straightness of the hole can also be checked. During inspection, it can be ensured that if there is any lack of straightness or roundness of the hole a full entry of the GO plug gauge will not be allowed. Thus, it not only controls the diameter in any given cross-section but also ensures better bore alignment. However, it should be mentioned here that the

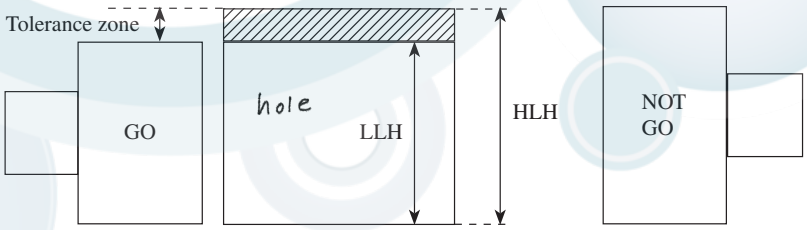


Fig. 3.22 GO and NOT GO limits of plug gauge

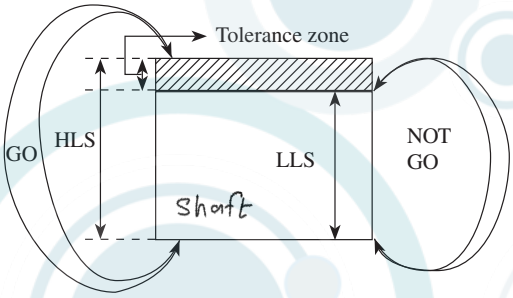


Fig. 3.23 GO and NOT GO limits of snap gauge

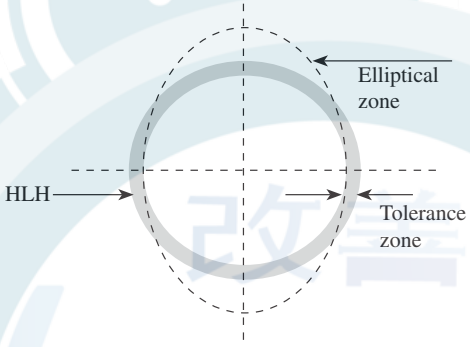


Fig. 3.24 Ovality in hole

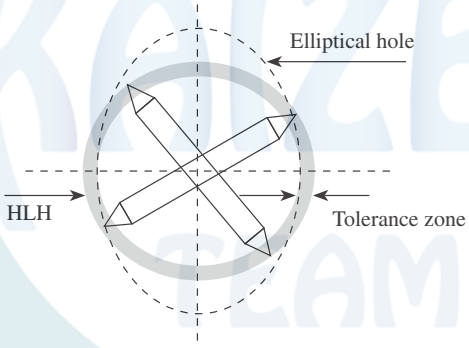


Fig. 3.25 Pin-type NOT GO to the check ovality

GO plug gauge cannot check the degree of ovality.

The short GO plug gauge, if used in inspection, will pass through all the curves and is hence not possible to identify defective parts. Therefore, in order to get good results, this condition has to be fulfilled during the inspection of the parts. The length of the plug should normally be more than 1.5 times the diameter of the hole to be checked. Compared to GO plug gauges, the NOT GO plug gauges are relatively shorter.

Let us consider the gauging of a cylindrical hole. A simple plug gauge is used to gauge this hole. During inspection, the GO gauge, which measures the minimum limit of the hole, enters but the NOT GO gauge, which corresponds to the maximum limit, does not. In this case, according to Taylor's theorem, the hole is considered to be within the specified limits and hence accepted. However, the shape of the hole has not been taken into account here. Most of the methods used in the manufacture of the holes are capable of producing truly circular holes. When these holes are gauged, they are accepted if they are within the specified tolerance zone. As long as there are no circularity errors, there is no problem. However, when the holes deviate from circularity, the problem starts. Consider an elliptical hole as shown in Fig. 3.24. It can be clearly observed from Fig. 3.24 that the NOT GO gauge does not enter because the minor axis of the ellipse is smaller than the HLH, which corresponds to the diameter of the NOT GO gauge. Therefore, even if the hole is slightly elliptical, the gauge does not take into account this variation of the hole shape and it still gets accepted as the GO gauge assembles and the NOT GO gauge does not.

One way of overcoming this problem is to employ the NOT GO, which is in the form of a pin. Any error in the circularity can easily be detected by placing the pin at different cross-sections of the hole, as depicted in Fig. 3.25. Hence, it can be said that Taylor's principle does not take care of the error of form, circularity, or straightness, and some modifications are needed to overcome these limitations.

3.6.5 Important Points for Gauge Design

The following points must be kept in mind while designing gauges:

1. The form of GO gauges should be a replica of the form of the opposed (mating) parts.

2. GO gauges enable several related dimensions to be checked simultaneously and hence are termed complex gauges.
3. During inspection, GO gauges must always be put into conditions of maximum impassability.
4. NOT GO gauges check a single element of feature at a time.
5. In inspection, NOT GO gauges must always be put into conditions of maximum passability.

3.6.6 Material for Gauges

The material used to manufacture gauges should satisfy the following requirements:

1. The material used in the manufacture of gauges should be hard and wear resistant for a prolonged life. This is one of the most important criteria that should be fulfilled.
2. It should be capable of maintaining dimensional stability and form.
3. It should be corrosion resistant.
4. It should be easily machinable, in order to obtain the required degree of accuracy and surface finish.
5. It should have a low coefficient of expansion, in order to avoid temperature effect.

High-carbon steel is the most suitable and inexpensive material used for manufacturing gauges. It can be heat treated suitably to provide stability and high hardness. It can easily be machined to a high degree of accuracy.

Mild steel gauges are the most suitable for larger gauges. They are suitably heat treated by carburizing to the required depth and then case hardened on their working surfaces to allow for final grinding and finishing. After hardening, internal stresses are relieved to improve stability.

Chromium-plated gauges are very popular and extensively used for gauging. Chromium plating makes the surface of the gauge very hard, and resistant to abrasion and corrosion. It is also very useful in reclaiming worn-out gauges. For gauging aluminium or other materials having an abrasive action, chromium-plated gauges are extensively used. The plug gauges employed for gauging have satellite ribs that are inserted in the gauging surface.

Glass gauges are not very popular although they have good wear and corrosion resistance properties. The problem with these gauges is that they either get damaged or are easily broken if dropped. They are not affected by changes in temperature and have very low coefficient of thermal expansion.

Although Invar, which contains 36% of nickel, has a low coefficient of expansion, it is not suitable over a long period. Elinvar has 42% of nickel, is more stable than Invar, and also has a low coefficient of expansion.

3.6.7 Gauge Tolerance (Gauge Maker's Tolerance)

We know that gauges have to be manufactured to their required dimensions corresponding to their maximum metal conditions. Gauges, like any other component, cannot be manufactured to their exact size or dimensions. In order to accommodate these dimensional variations, which arise due to the limitations of the manufacturing process, skill of the operator, etc., some tolerance must be allowed in the manufacture of gauges. Thus, the tolerance that is allowed in the manufacture of gauges is termed *gauge maker's tolerance* or simply *gauge tolerance.* Logically, gauge tolerance should be kept as minimum as possible; however, this increases the gauge manufacturing cost. There is no universally accepted policy for deciding the amount of

tolerance to be provided on gauges. The normal practice is to take gauge tolerance as 10% of the work tolerance.

3.6.8 Wear Allowance

As discussed in Section 3.6.4, according to Taylor's principle, during inspection the NOT GO side should not enter or pass. The NOT GO gauge seldom engages fully with the work and therefore does not undergo any wear. Hence, there is no need to provide an allowance for wear in case of NOT GO gauges.

Taylor's principle also states that the GO side of the gauge should enter the hole or just pass over the shaft under the weight of the gauge without using undue force. During inspection, the measuring surfaces of the gauge constantly rub against the mating surfaces of the workpiece. Therefore, the GO gauges suffer wear on the measuring surfaces and thus lose their initial dimension. Hence, wear allowance is provided for GO gauges to extend their service life. As a consequence of this wear, the size of the GO plug gauge decreases while that of the ring or gap gauge increases. The wear allowance provided for the GO gauges are added in a direction opposite to wear. This allowance is added in for a plug gauge while subtracted for a ring or gap gauge. A wear allowance of 10% of gauge tolerance is widely accepted in industries. If the work tolerance of a component is less than 0.1 mm, no wear allowance on gauges is provided for that component, since a wear allowance of less than 0.001 mm will not have any practical effect on the gauges.

The allowance on new gauge is made by fixing the tolerance zone for the gauge from the MML of the work by an amount equal to the wear allowance. A new gauge is then manufactured within the limits specified by the tolerance zone for the gauge in this position. The gauge is then allowed to wear with use until its size coincides with the maximum material limit for the work.

3.6.9 Methods of Tolerance Specification on Gauges

if the part is rejected by the tolerance of workshop gauges → will use the inspection gauge, if it's acceptable by the inspection gauge → then it's rejected because of the tolerance of the workshop gauges not because the item itself.

By considering all the important points of gauge design, tolerances on gauges (snap and plug gauges) are specified by the following three methods.

First Method

This method of specifying tolerances on gauges was evolved during the developmental stages of gauges. In this system, the tolerance zones of workshop and inspection gauges are different and are made separately. Here the tolerances on the workshop gauge are set to fall inside the work tolerance, whereas the inspection gauge tolerances fall outside the work tolerance.

In workshop gauges, the tolerance on GO and NOT GO gauges is 10% of the work tolerance. For example, if the work tolerance is 10 units, then only 8 units will be left as the difference between maximum limit of GO gauge and minimum limit of NOT GO gauge, since these tolerances fall inside and are 1 unit each, as shown in Fig. 3.26. For inspection gauges, it can be seen that the tolerance on gauges is kept beyond 10% of work tolerance.

Disadvantages of workshop and inspection gauges:

1. Although some of the components are well within the work tolerance limits, they may be rejected under workshop gauges. These components again need to be checked by inspection gauges and may be accepted after that.

Go → unilateral tolerance.

2. It may also happen that some of the components when tested by inspection gauges may get accepted.
3. As the tolerance zones are different, both workshop and inspection gauges have to be manufactured separately.

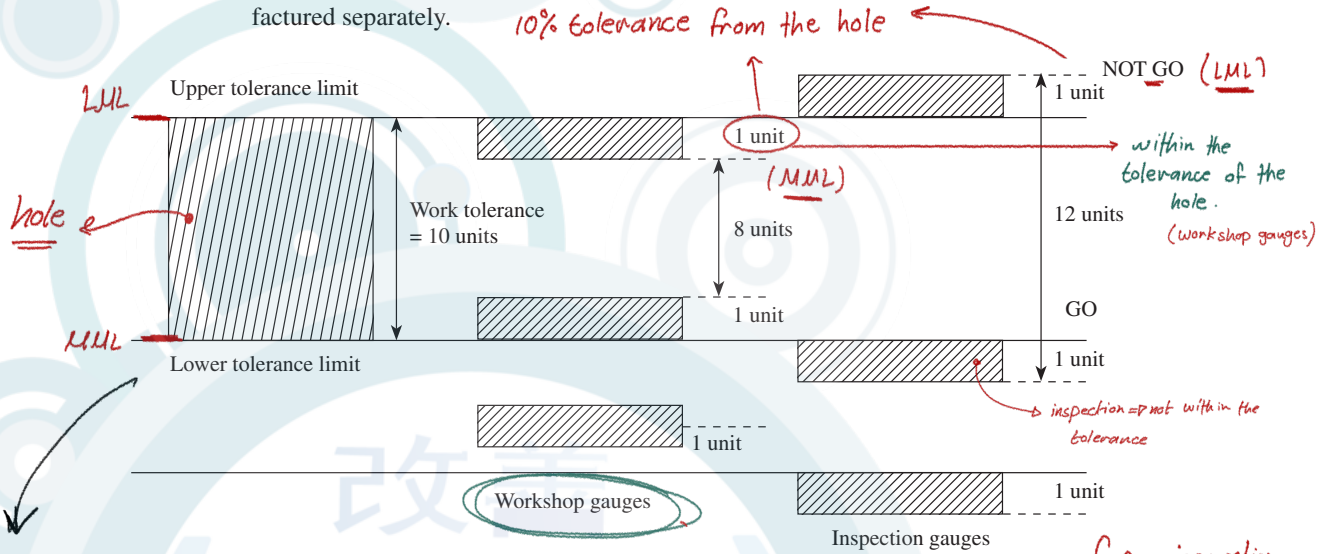


Fig. 3.26 Disposition of tolerances on workshop and inspection gauges

to check the source of the tolerance.
↳ another GO/NOT GO with Tolerance not within the tolerance of the hole.

Revised System of Gauges

In this system, the tolerance zone on inspection gauges is reduced and the tolerance on workshop gauges is retained as before. The disadvantages of inspection gauges are reduced due to the reduction of tolerance on these gauges. It can be observed from Fig. 3.27 that instead of 120% of the tolerance provided in the first system for GO and NOT GO inspection gauges, in the revised system, 110% of the range of work tolerance is provided.

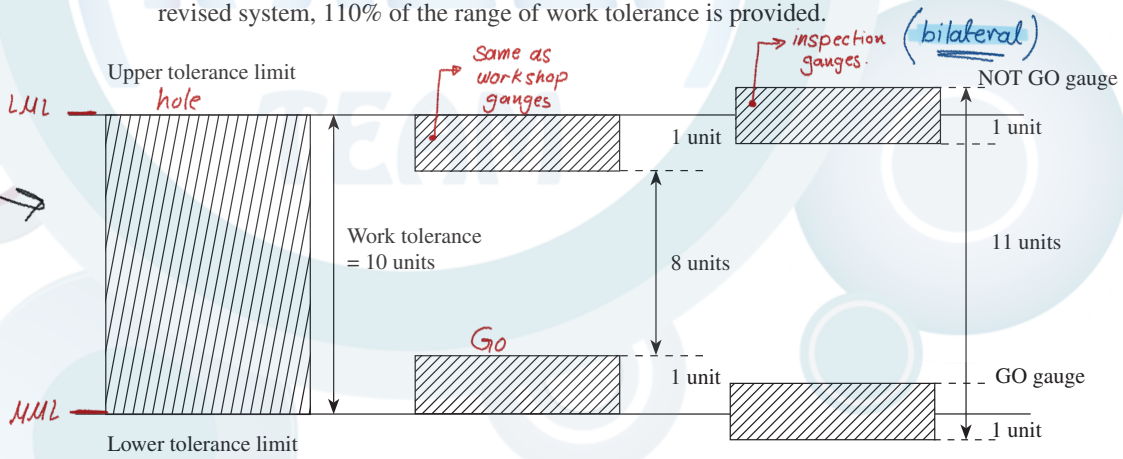


Fig. 3.27 Disposition of modified tolerances on workshop and inspection gauges

** Same as method (1) but the difference is in the first method the inspection gauges are unilateral tolerance but in Revised it bilateral tolerance.

two differences
- Only one pair for inspection (not workshop & inspection)

British System

The present British system is in accordance with Taylor's principle and is widely accepted in industries. This system works according to the following guidelines:

1. The specified tolerance should be wide and, at the same time, consistent with satisfactory functioning, economical production, and inspection.
2. During inspection, the work that lies outside the specified limits should not be accepted.

Thus, in this modern system, the same tolerance limits are specified on workshop and inspection gauges, and the same gauges can be used for both purposes.

It can be observed from Fig. 3.28 that the tolerance zone for the GO gauges is placed inside the work limits and that for the NOT GO gauges is outside the work limits.

A margin is provided in between the tolerance zone for the gauge and MML of the work to accommodate wear allowance for GO gauges. It is to be noted here that wear allowance should not be permitted beyond the MML of the work, especially when the limit is of critical importance. The magnitude of wear allowance is 10% of the gauge tolerance.

wear عكس ال
tolerance 10% from hole tolerance + 10% from its tolerance.
hole, Go sh., shaft
2 shaft → inspection (hole)
2 hole → " (Shaft).

3.6.10 Numerical Examples

Example 3.7 Design the general type of GO and NOT GO gauges as per the present British system for a 40 mm shaft and hole pair designated as 40 H8/d9, given that

(a) $i = 0.453\sqrt[3]{D} + 0.001D$
(b) 40 mm lies in the diameter range of 30–50 mm
(c) IT8 = 25i
(d) IT9 = 40i
(e) upper deviation of shaft = $-16D^{0.44}$ (below the Basic)
(f) wear allowance assumed to be 10% of gauge tolerance

tolerance لا يقع not within the limits

* Tolerance of the gauge = 10% Tolerance of the wp.
* Movement from the basic size = 10% Tolerance of the gauge.
  → 1% Tolerance of wp. (wear allowance).
wear يكون عكس ال

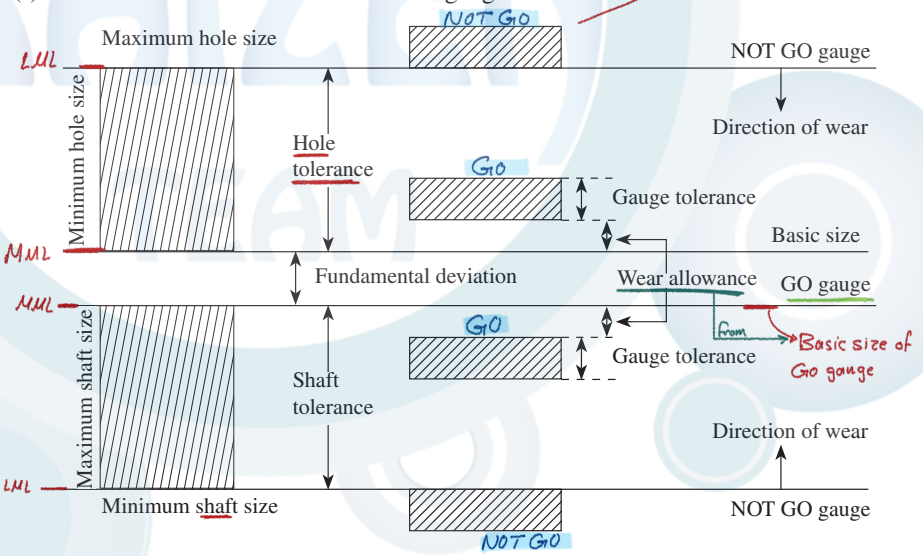
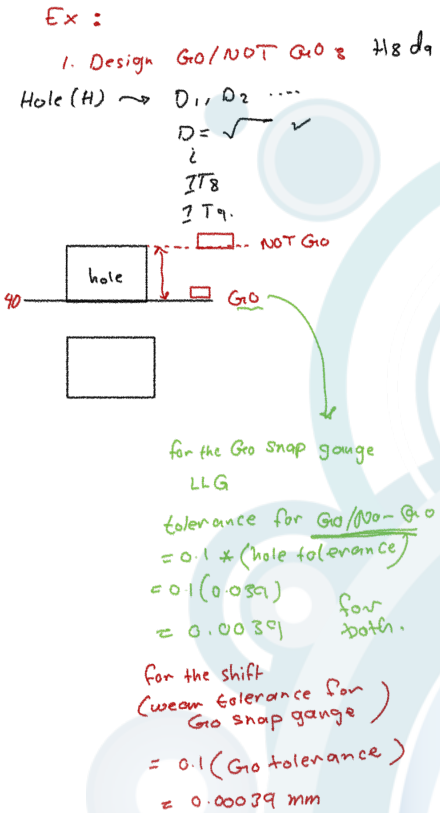


Fig. 3.28 Disposition of tolerances and allowances on gauges



Solution

The standard diameter steps for 40 mm shaft falls in the range of 30–50 mm.

D can be calculated using the equation $\sqrt{D_{max} \times D_{min}}$.

Therefore,

$$D = \sqrt{30 \times 50}$$

$$D = 38.7298 \text{ mm}$$

The value of fundamental tolerance unit is given by

$$i = 0.453 \sqrt[3]{D} + 0.001D$$

$$i = 0.453 \left(\sqrt[3]{38.7298} \right) + 0.001(38.7298) = 1.571 \text{ µm}$$

For hole quality H8, the fundamental tolerance is $25i$.

$$25i = 25(1.571) = 39.275 \text{ µm} = 0.039275 \text{ mm} \approx 0.039 \text{ mm}$$

For hole, the fundamental deviation is zero.

Hence, hole limits are as follows:

LLH = 40 mm

HLH = 40.00 + 0.039 = 40.039 mm

Hole tolerance = 40.039 – 40 = 0.039 mm

For shaft quality $d9$, the fundamental tolerance is $40i$.

$$40i = 40(1.571) = 62.84 \text{ µm} = 0.06284 \text{ mm} \approx 0.063 \text{ mm}$$

For d shaft, the fundamental deviation is given by $-16D^{0.44}$

Therefore, fundamental deviation $= -16(38.7298)^{0.44}$

$= -79.9576 \text{ µm} \approx -0.07996 \text{ mm} \approx -0.080 \text{ mm}$

Hence, shaft limits are as follows:

HLS = 40 – 0.080 = 39.92 mm

LLS = 40 – (0.080 + 0.063) = 39.857 mm

Shaft tolerance = 39.92 – 39.857 = 0.063 mm

Hence, the hole and shaft limits are as follows:

$$\text{Hole} = 40^{+0.039}_{+0.000} \text{ mm and shaft} = 40^{-0.080}_{-0.143} \text{ mm}$$

The disposition of tolerances is as shown in Fig. 3.29.

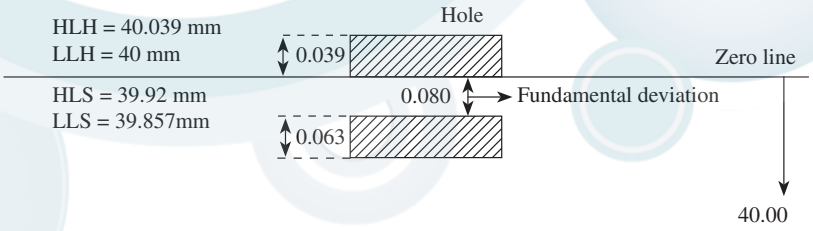


Fig. 3.29 Disposition of tolerances

Assuming gauge tolerance to be 10% of work tolerance,
gauge tolerance for hole = 10% of 0.039 = 0.0039 mm
Wear allowance for hole = 10% of Gauge tolerance; therefore,
Therefore, wear allowance for hole = 10% of 0.0039 = 0.00039 mm

Similarly,
Gauge tolerance for shaft = 10% of 0.063 = 0.0063 mm
Wear allowance for shaft = 10% of 0.0063 = 0.00063 mm

For hole:
The limits of GO Plug gauge are as follows:
Low limit = Basic size + Wear allowance
Low limit = 40.00 + 0.00039 = 40.00039 mm
High limit = Basic size + (Wear allowance + Gauge tolerance)
High limit = 40.00 + (0.00039 + 0.0039) mm
= 40.00 + (0.00429) = 40.00429 mm

Limits of GO plug gauge = $40\ ^{+0.00429}_{+0.00039}$ mm
The limits of NOT GO Plug gauge are as follows:
Low limit = Basic size + Fundamental tolerance for hole
Low limit = 40.00 + 0.039= 40.039 mm
High limit = Basic size + (Fundamental tolerance for hole + Gauge tolerance)
High limit = 40.00 + (0.039 + 0.0039) mm
= 40.00 + (0.0429) = 40.0429 mm

Limits of NOT GO plug gauge = $40\ ^{-0.0429}_{+0.0390}$ mm
For shaft:
The limits of GO snap gauge are as follows:
High limit = Basic size − (Fundamental deviation + Wear allowance)
High limit = 40.00 − (0.080 + 0.00063) mm
High limit = 40.00 − (0.08063) = 39.91937 mm
Low limit = Basic size − (Fundamental deviation + Wear allowance + Gauge tolerance)
Low limit = 40.00 − (0.080 + 0.00063 + 0.0063) mm
= 40.00 − (0.08693) = 39.91307 mm

Limits of GO snap gauge = $40\ ^{-0.08063}_{-0.08693}$ mm
Limits of NOT GO snap gauge are as follows:
High limit = Basic size − (Fundamental deviation + Fundamental tolerance)
High limit = 40.00 − (0.080 + 0.063) mm
High limit = 40.00 − (0.143) = 39.857 mm
Low limit = Basic size − (Fundamental deviation + Fundamental tolerance + Gauge tolerance)
Low limit = 40.00 − (0.080 + 0.063 + 0.0063) mm
Low limit = 40.00 − (0.1493) = 39.8507 mm

Limits of NOT GO snap gauge = $40\ ^{-0.1430}_{-0.1493}$ mm

The disposition of gauge tolerances and wear allowance for the GO and NOT GO plug and snap gauge are schematically shown in Fig. 3.30.

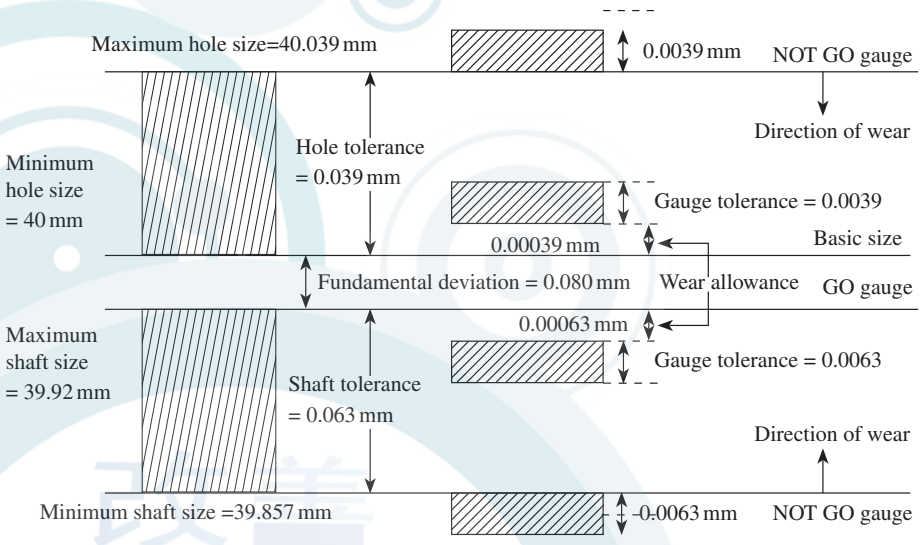


Fig. 3.30 Disposition of gauge tolerances and wear allowance

3.7 PLAIN PLUG GAUGES

Gauges that are used for gauging holes are known as plug gauges. Plain plug gauges are manufactured using hardened and stabilized wear-resistant steel. The gauging surface of the plug gauges are ground and lapped to make it smooth. The surface of these gauges is hardened to not less than 750 HV. Handles for these plug gauges may be made using any suitable steel. Handles made from light metal alloys can be used for heavy plain plug gauges. For smaller plain plug gauges, handles can be made using a suitable non-metallic material. Double-ended-type plug gauges for sizes up to 63 mm and single-ended-type gauges for sizes above 63 mm are recommended as standards. In order to protect the plug gauges against climatic conditions, they are normally coated with a suitable anticorrosive coating.

Plain plug gauges are designated by specifying

1. nominal size
2. 'GO' and 'NOT GO' on the GO and NOT GO sides, respectively
3. class of tolerance of the workpiece to be gauged
4. the manufacturer's name and trademark
5. marking the NOT GO side with a red colour band to distinguish it from the GO side, irrespective of whether the gauge is single or double ended

For example, if the plain plug is designated (according to Indian standard IS: 3484) as 'GO and NOT GO plain plug gauge 40 H7, IS: 3484', it means that it is a plain plug gauge for gauging a bore having a nominal size of 40 mm with a tolerance of H7 and is as per Indian standard.

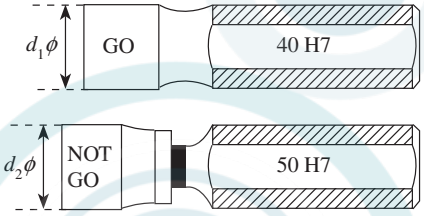


Fig. 3.31 Single-ended GO and NOT GO plug gauges

Single- and double-ended plug gauges are shown in Figs 3.31 and 3.32, respectively. The GO side is made to the lower limit of the hole represented by diameter d_1. The NOT GO side is made to a size equal to the upper limit of the hole represented by diameter d_2. A progressive type of plug gauge is shown in Fig. 3.33. In this type, both GO and NOT GO gauges are on the same side. This can be conveniently used to gauge smaller through holes. During gauging, the GO side of the gauge assembles to its full length. As the gauge is moved further, the NOT GO side obstructs the entry of the gauge into the hole.

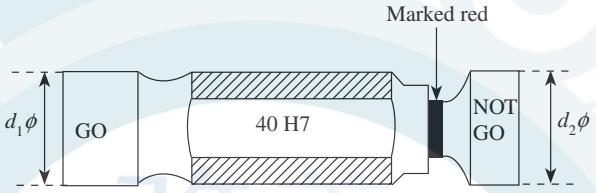


Fig. 3.32 Double-ended plug gauges

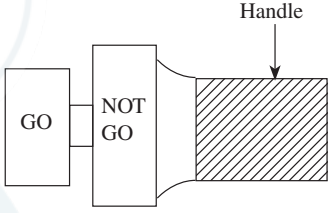


Fig. 3.33 Progressive plug gauges

3.8 SNAP GAUGES

Snap gauges are used to gauge the shaft to ascertain whether the dimensions of the shafts are well within the tolerance limits. These gauges like plug gauges are also manufactured using hardened and stabilized wear-resistant steel. The gauging surface is ground and lapped. Shafts of sizes ranging from 3 to 100 mm can conveniently be gauged using double-ended snap gauges, as shown in Fig. 3.34. For sizes over 100 and up to 250 mm, single-ended progressive-type snap gauges are used. A progressive snap gauge is schematically represented in Fig. 3.35.

test a shaft ⇝ snap
a hole ⇝ plug

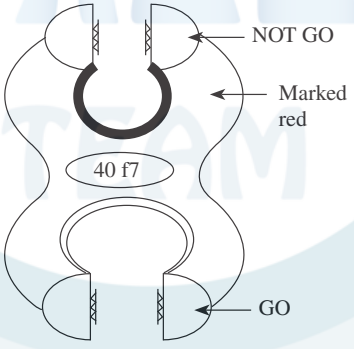


Fig. 3.34 Double-ended snap gauge

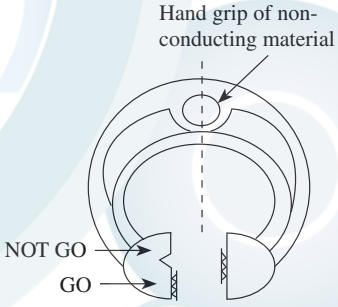


Fig. 3.35 Progressive snap gauge

A QUICK OVERVIEW

- No component can be manufactured precisely to a given dimension; it can only be made to lie between the upper and lower limits. The designer has to suggest these tolerance limits, which are

Chapter (3) : Limits, Fits & Tolerances.

* Assignable causes : variability which is not a part of random or chance cause pattern
  - easily be identified & controlled
  - Large variability between the Samples

Random causes : acceptable variability.

* No difficulty when the tolerance allowed greater than the process variation

(3.3) Tolerance : magnitude of premissible variation of dimension, or

Total variation permitted in the size ⟹ the algebric difference between upper & lower acceptable dim. always (+ve).

* as tolerance decrease (numerical value) ⟹ cost of manufacturing increases.

** Classification of tolerance :

1. Unilateral Tolerance : only in one side tolerance (above or below).

$^{+0.02}_{+0.01}$ / $^{+0.02}_{-0.00}$ / $^{-0.01}_{-0.02}$ / $^{+0.00}_{-0.02}$

2. Bilateral : on either side / Both sides not necessarily equally disposed.

3. Compound : more than one dimension.

4. Geometric : used to indicate the relationship of one part with another.

types:

A. Form : for individual Features, independent tolerance.
   - Geometric characteristic : Straightness / Circularity / Flatness / Cylindricity.

B. Orientation : limit the direction or orientation., Related tolerance.
   - Geometric characteristic : Perpendicularity / Parallelism / Angularity.

C. Positional tolerance : controls the extent of deviation., Related Tolerance, 3D
   - Geometric characteristic : Position(3D) / Symmetry (3D) / Concentricity (3D).

Ex: $L_A = 30^{+0.02}_{-0.01}$, $L_B = 20^{+0.02}_{-0.01}$, $L_C = 10^{+0.02}_{-0.01}$

the overall length = 60
upper tolerance = + (0.06)
lower " = − (0.01)

$60^{+0.06}_{-0.01}$

* essential to avoid or minimize the cumulative effect of tolerance build-up
  - by common reference line or base line

(3.4) Maximum & Minimum metal Conditions.

* Shaft ⟨ HLS : MML / LLS : LML
* Hole ⟨ HLH : LML / LLH : MML

(3.5) Fits : relationship between parts that are to be assembled

(hole & shaft with respect to the difference in their dim before assembly).

1. **Clearance Fit** (↓ easily assembled.): is the largest diameter of the Shaft is smaller than the diameter of the smallest hole ?

min. dia. hole > max. dia. Shaft

max. clearance : HLH − LLS

min. clearance : LLH − HLS

2. **Interference Fit** (↓ tight fit.): is the minimum diameter of the shaft exceed the max. diameter of the hole ?

min. (Shaft) > max. (hole).

* permanent, with heating or cooling, difference between sizes = (−ve).

max. interference = HLS − LLH

min. interference = LLS − HLH

3. **Transition :** Largest hole > Smallest shaft ⇝ C. ⇝ LML (hole) with LML (Shaft) : clearance

smallest hole < Largest shaft. ⇝ I ⇝ MML (hole) with MML (Shaft) ; interference.

** Allowance : The intentional difference between (LLH) & (HLS), could be (+ve) or (−ve).

Allowance = LLH − HLS

** Hole Basis sys. ⇝ the fundamental deviation or Lower deviation = Zero

LLH = Basic Size. EI = Zero

** Shaft Basis sys. ⇝ the fundamental deviation or the upper deviation = Zero.

HLS = Basic size es = zero

* Numerical Examples.

1. Hole = $30^{+0.02}_{+0.00}$, Shaft = $30^{-0.02}_{-0.05}$ ⇝ 1. Tolerance : hole = 0.02 , shaft = 0.03.
2. Allowance : 0.02

2. Hole = $25^{+0.03}_{-0.00}$, Shaft = $25^{-0.006}_{-0.02}$ ⇝ Tolerance hole = 0.03 , Shaft = 0.014
Allowance = 0.006
max clearance = 0.05
min " = 0.006

3. Hole = $50^{+0.02}_{-0.00}$, Shaft = $50^{-0.05}_{-0.08}$ ⇝ max. clearance = 0.1
min " = 0.05
Tolerance : hole = 0.02, shaft = 0.03
Allowance = 0.05

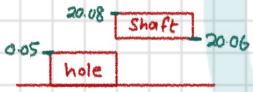
4. Example 3.4.

5. Hole = $20^{+0.025}_{+0.000}$, Shaft = $20^{+0.08}_{+0.005}$ ⇝ Tolerance : hole = 0.025 , shaft = 0.075



⇝ transition fit. ⇒ HLH − LLS = +ve clearance
LLH − HLS = −ve interference] ⇒ transition fit.

6. Hole = $20^{+0.05}_{+0.00}$, Shaft = $20^{+0.08}_{+0.06}$ ⇝ Tolerance hole = 0.05 mm , shaft = 0.02 mm.



⇝ HLH − LLS = −ve
LLH − HLS = −ve] interference fit

(3.6) System of Limits & Fits :

Es = HLH − Basic
EI = LLH − Basic] ⇒ Tolerance = HLH − LLH = Es − EI

es = HLS − Basic
ei = LLS − Basic] ⇒ Tolerance = HLS − LLS = es − ei

① $\sqrt{D_1 * D_2} = D$

② $i = 0.453\,(D)^{\frac{1}{3}} + 0.001D$ in μm

③ Standard tolerance in μm / 1000.

Table (3.5) : $es(a) = EI(A)$ ⇝ the fundamental values.

(3.7) General terminology :

Basic size : size in relation to which all limit are derived. ⇝ size based on which the dimensional deviations are given.

Limit of the size : max. & min. size acceptable.

Tolerance : variation of the size of a dimension ⇝ difference between the max. & min. limits of size ⇒ always (+ve).

Allowance : intentional difference between LLH & HLS ⇝ Allowance = LLH − HLS

Grade : indication of tolerance magnitude.

Deviation : algebraic difference between size & corresponding basic size

Fundamental deviation : min. difference between the size of the component & it's basic size
⇝ closet deviation of the basic size

Fit : relationship that exist between two mating parts with the respect to their dimensional difference before assembly.

Example : Design an easy Running fit for a Basic size = 130 mm.

* from table (3.2) the class of fit for (easy running) ⟹ H8/f8.

1 for the Hole (H8) → table 3.5

⟹ Basic size = 130 mm → 120 – 180 → $D_1 = 120$ $D_2 = 180$

$D = \sqrt{120 * 180} = 146.96$

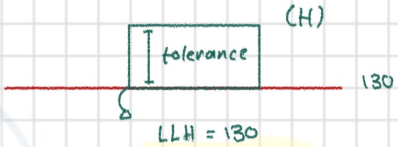
for hole ← $i = 0.45 (D)^{\frac{1}{3}} + 0.001D \Rightarrow 0.45 (146.96)^{\frac{1}{3}} + (0.001 * 146.96)$

$= 2.52 \mu m$

⟹ Find the tolerance : $IT_8 = 25 * i \rightarrow 25 * (2.52) = 63.04 \mu m$ / 1000

$= 0.06304$ mm.

↳ hole tolerance



& since f8 ⟹ IT_8 : then tolerance of

→ LLH = 130, HLH = 130.063] EI = Zero, ES = HLH – Basic = tolerace = 0.06304.

* The fundamental = EI = Zero

→ For the Shaft ;

$IT_8 = 0.06304$ From table 3.5 → The fundamental deviation es.

The fundamental is the upper deviation of the shaft. ← $es = -5.5 D^{0.41} = -5.5 * (146.96)^{0.41}$, $es = -42.55 \mu m$

$es = -0.04255$ mm

$es = HLS - Basic \rightarrow -0.04255 = HLS - 130$

$HLS = 129.95745$ mm

to find LLS ; Tolerance = HLS – LLS

$-0.06304 = 129.95745 - LLS$

$LLS = 129.89445$ mm

or Tolerance = es – ei

= HLS – LLS

Example : Design a Loose fit for a Basic = 121 mm :

from table 3.2 ⇒ Loose fit = H8dq ← 120 – 180.

① for the hole : (H8)

* $D = \sqrt{120 * 180} = 146.96$ mm

** $i = 0.45(146.96)^{\frac{1}{3}} + 0.001D = 2.52\ \mu m$.

*** $IT_8 = 25(i) = 25 * 2.52 = 63.04\ \mu m = 0.06304$ mm ⇝ for the hole.

$IT_q = 40(i) = 40 * 2.52 = 100.8\ \mu m = 0.1008$ mm ⇝ for the shaft

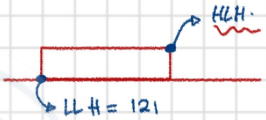
fundamental : lower value.

H8 : E_I = Zero (fundamental).

From table 3.5 ⇒ e_s (shaft) = E_I (hole)

E_s : Tolerance = $E_s - E_I$ $E_s = 0.06304$

HLH = LLH + Tolerance = 121.06304



* LLH = E_I + Basic

HLH = 121.063 mm LML

LLH = 120.00 mm HML

② For the Shaft (dq).

fundamental ← $e_s = -16(D)^{0.44} = -16 * (146.96)^{0.44} = -143.77\ \mu m = -0.143776$ mm ⇝ from table 3.5.

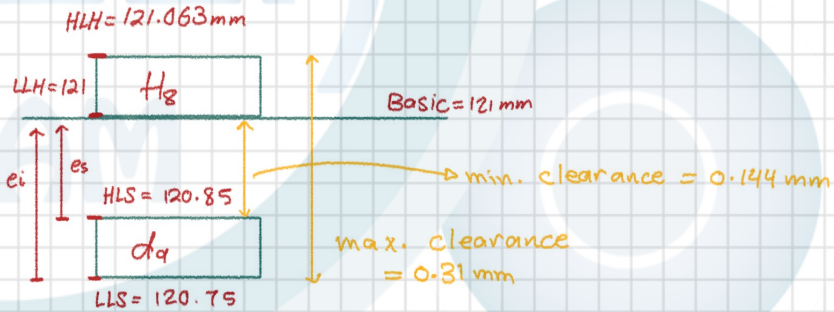
Tolerance = $e_s - e_i$ ⇒ $e_i = -0.143776 - 0.1008$

$e_i = -0.24457$ mm

e_i = LLS – Basic ⇒ LLS = –0.24457 + 121 = 120.77 mm LML

e_s = HLS – Basic = –0.143776 + 121 =

HLS = 120.856 mm MML



Question 1 **12 points**

For a shaft and a hole system of (85 H7- k6)
Given

The diameter steps are $D_1 = 80$ mm, $D_2 = 120$ mm

$$D = \sqrt{D_1 * D_2}$$

$$i = 0.453 * \sqrt[3]{D} + 0.001 * D \qquad where\ D\ is\ in\ mm, and\ i\ is\ in\ \mu m$$

The fundamental deviation of **shaft k** is $\boldsymbol{ei} = +(\mathbf{0.6} * \sqrt[3]{D})$
where (D) is in mm, and (ei) is in µm

$$IT\,6 = 10 * i$$
$$IT7 = 16 * i$$

$D = \sqrt{80 * 120} = 97.97$ mm

$i = (0.45)(97.97)^{\frac{1}{3}} + 0.001(97.97)$

$i = 2.172\ \mu m$

Tolerance, hole = $16(i) = 34.76\ \mu m$
$= 0.0347$ mm

shaft = $10(i) = 0.02172$ mm.

for the hole:

EI = zero ⇒ LLH = 85 mm



Tolerance = $ES - EI$

$ES = 0.0347$ mm.

HLH = $0.0347 + 85$

HLH = 85.0347 mm

* fundamental deviation = EI = zero

for the shaft

$ei = +0.6\,(97.97)^{\frac{1}{3}}$ ⇒ $ei = 0.00276$ mm.

Tolerance = $es - ei$ ⇒ $es = 0.02172 + 0.00276$

$es = 0.02448$ mm

es = HLS − Basic ⇒ HLS = $0.02448 + 85$

HLS = 85.02448 mm

ei = LLS − Basic ⇒ LLS = $0.00276 + 85$

LLS = 85.00276 mm

* The fundamental of the shaft = lower deviation = 0.00276

* Basic أقرب لـ

A. Calculate the following

1. **The higher limit of the hole (HLH)**
2. **The lower limit of the hole (LLH)**
3. **The upper deviation of the hole (ES)**
4. **The lower deviation of the hole (EI)**
5. **The fundamental deviation of the hole**
6. **The higher limit of the shaft (HLS)**
7. **The lower limit of the shaft (LLS)**
8. **The upper deviation of the shaft (es)**
9. **The lower deviation of the shaft (ei)**
10. **The fundamental deviation of the shaft**

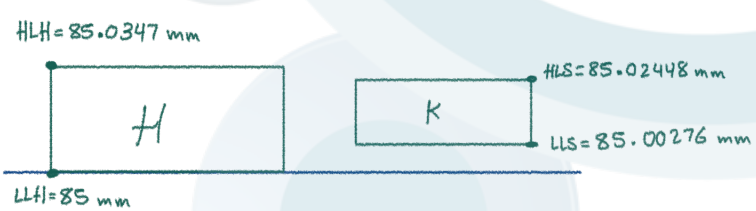
B. Draw a simple sketch for the shaft and hole system

C. What is the type of fit between the shaft and the hole. Explain your answer.

↳ not clearance because the min. dia. of the hole not higher than the max. dia. of the shaft.

& not interference. because the min. dia. of the shaft is not higher than the max. dia of the hole.

⟹ it's a transition fit.



Example 3.2 The following limits are specified in a limit system, to give a clearance fit between a hole and a shaft:

Hole = $25^{+0.03}_{-0.00}$ mm and shaft = $25^{-0.006}_{-0.020}$ mm

Determine the following:

(a) Basic size

(b) Tolerances on shaft and hole

(c) Maximum and minimum clearances

* Tolerance = ES − EI

= upper deviation − lower deviation

Hole = $25^{+0.03}_{-0.0}$ mm , Shaft = $25^{-0.006}_{-0.020}$

① Basic size = 25 mm

② Tolerance : shaft = −0.006 − (−0.020) = 0.014 mm

hole = 0.03 mm

③ Maximum & minimum clearance.

Max. clearance = HLH − LLS = 25.03 − 24.98 = 0.05

Min. clearance = LLH − HLS = 25.00 − 24.994 = 0.006.

Example 3.4 A clearance fit has to be provided for a shaft and bearing assembly having a diameter of 40 mm. Tolerances on hole and shaft are 0.006 and 0.004 mm, respectively. The tolerances are disposed unilaterally. If an allowance of 0.002 mm is provided, find the limits of size for hole and shaft when (a) hole basis system and (b) shaft basis system are used.

Basic = 40 mm ,

Tolerance : hole = 0.006 mm

Shaft = 0.004 mm

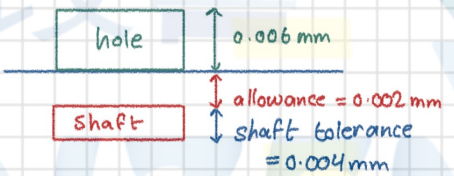
↳ unilaterally

Allowance = 0.002 mm

* Allowance : The lower limit of the hole is greater than the higher limit of the shaft

Allowance = LLH − HLS = 0.002

a.) Hole basis sys.



* For the hole :

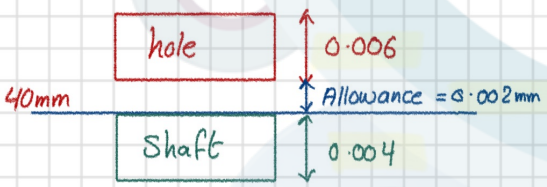
LLH = Basic size ⇒ because it's hole basis system = 40 mm.

HLH = Basic + tolerance = 40.006 mm

* For the Shaft :

HLS = LLH − allowance = 40 − 0.002 = 39.998 mm

LLS = HLS − Tolerance = 39.998 − 0.004 = 39.994 mm



b) Shaft basis system.

* For the Shaft -

HLS = 40mm ⟶ Shaft basis sys.

LLS = HLS − Tolerance = 40 − 0.004 = 39.996 mm

* For the hole .

LLH − HLS = Allowance ⟶ LLH = 0.002 + 40

= 40.002 mm

HLS = LLS + Tolerance = 40.002 + 0.006

= 40.008 mm

Question 1:

For a shaft and a hole system of (25 N7-h6)

Given

D1= 24mm, D2=30mm

$i = 0.45 * \sqrt[3]{D} + 0.001 * D$ *where D is in mm, and i is in µm*

The fundamental deviation of **shaft n** is $(ei = +5D^{0.34})$

IT6 = 10 *i

IT 7= 16* i

1. Calculate the following for both the shaft and the hole.
   a. Lower deviation
   b. Upper deviation
   c. Fundamental deviation
   d. Lower limit
   e. Upper limit
   f. Tolerance
   g. The minimum allowance
   h. The maximum allowance

2. Draw a sketch for the system above including the values you have calculated in 1.

$D = \sqrt{24 * 30} = 26.832$ mm

$i = 0.45 (26.832)^{\frac{1}{3}} + 0.001(26.832)$
$= 1.374$ µm
$= 0.001374$ mm.

Tolerance hole = $16 * i = 0.0219$ mm
" Shaft = $10 * i = 0.0137$ mm.

for the hole : $Es = -5(D^{0.34})$
$= -5 * (26.83)^{0.34}$
$= -15.3$ mm.
$= -0.0153$ mm

Es = HLH − Basic ⇝ HLH = Es + Basic
↳ fundamental deviation ⇒ closer to the Basic.

HLH = 24.984 mm

Tolerance = HLH − LLH ⇒ LLH = HLH − tolerance

LLH = 24.962 mm.

Tolerance = $Es - EI$ ⇒ $EI = Es - Tolerance$

$EI = -0.0372$ mm

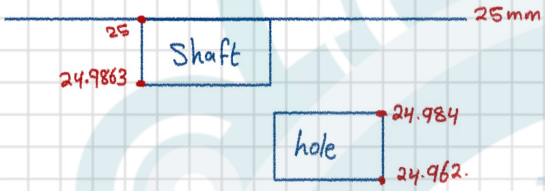
For the Shaft :

es = zero = fundamental
Tolerance = 0.0137 mm.

ei = es − tolerance = −0.0137 mm.

HLS = 25
LLS = HLH − tolerance = 24.9863 mm

* it's a shaft basis sys.



Max. allowance = LLH − HLS = 24.962 − 25
= −0.038 mm

Min allowance = HLH − LLS

8. Dec.

test a shaft ⇝ snap gauges
test a hole ⇝ plug "

Shaft & hole system (25 $H_7 n_6$)

$D_1 = 18$ mm , $D_2 = 30$ mm ⇝ $D = \sqrt{18 * 30} = 23.23$ mm ... (1).

$i = 0.453 \sqrt[3]{23.23} + 0.001 (23.23) = 0.001315$ mm. ... (2)

$IT_7 = 16 (0.001315) = 0.021$ mm ⇝ Tolerance of the hole.

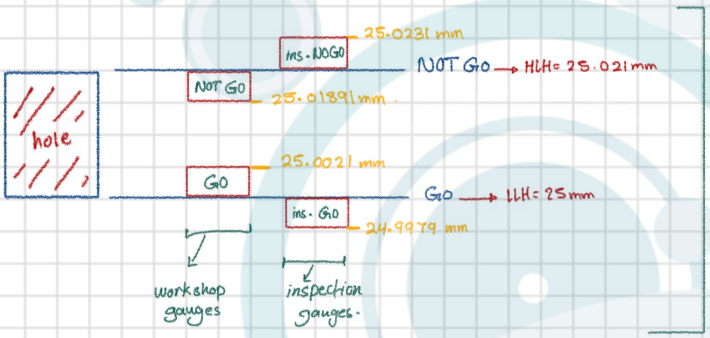
$IT_6 = 10 (0.001315) = 0.01315$ mm ⇝ Tolerance of the shaft. ... (3)

1 For the hole :

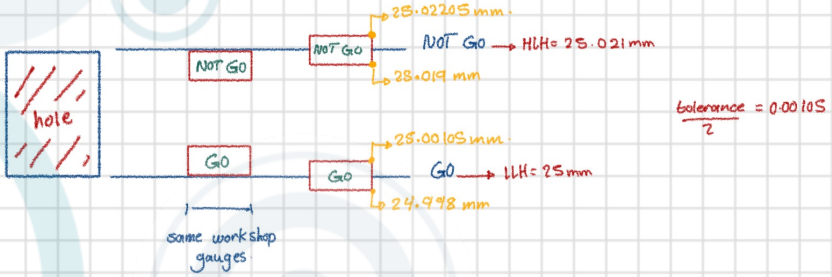
$EI = 0$, LLH = 25 mm , HLH = 25.021 mm. , Tolerance = 0.021 mm

Tolerance of the gauge (Shaft) ⇝ 10% (hole tolerance) = $0.1 * (0.021) = 0.0021$ mm

① Method one :



② Revised method :

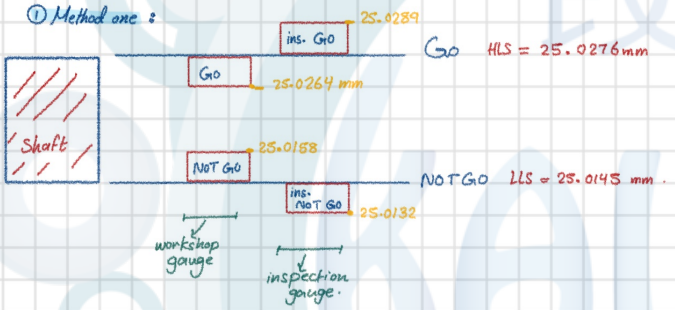


2 For the Shaft (n_6) :

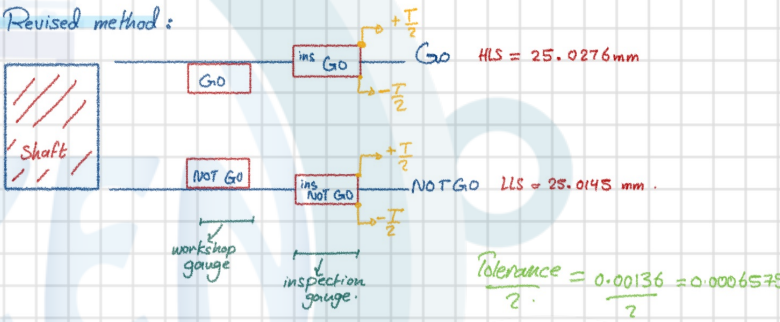
$ei = 5 (23.23)^{0.34} = 14.56$ Mm = 0.0145 mm ⇝ LLS = 25.0145 , Tolerance = 0.01315 , Tolerance of the gauges = 0.001315 mm.

HLS = 25.0276 mm.

① Method one :

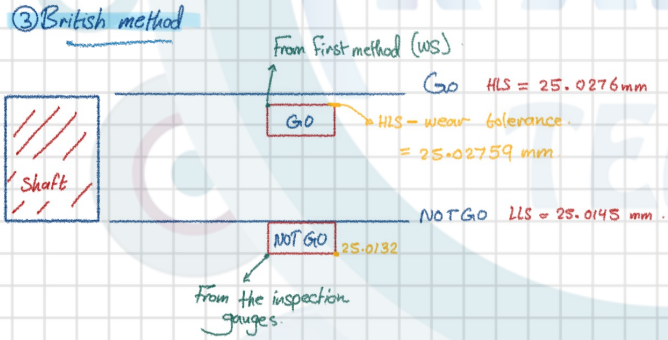


② Revised method :



Tolerance / 2 = 0.00136 / 2 = 0.000675

③ British method

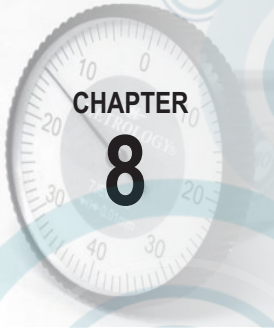


* For the GO gauge ⇝ wear tolerance = 0.1 (gauge tolerance)

= 0.1 (0.1 * shaft tolerance)

= 0.0001316 mm.

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CHAPTER

8

Metrology of Gears and Screw Threads

After studying this chapter, the reader will be able to

- understand the basic principles of measurement of gears and screw threads
- throw light on the geometry of spur gears and screw threads
- elucidate the measurement techniques used for the measurement of runout, pitch, profile, lead, backlash, and tooth thickness of spur gears
- analyse the various gear-measuring instruments such as gear-measuring machine, gear tooth calliper, tooth span micrometer, and Parkinson gear tester.
- explain the measurement principles of major diameter, minor diameter, effective diameter, pitch, angle, and form of screw threads.
- describe thread-measuring instruments such as bench micrometer, floating carriage micrometer, and pitch-measuring machine
- discuss the types and use of thread gauges for screw thread inspection

8.1 INTRODUCTION

Gears are the main elements in a transmission system. It is needless to say that for efficient transfer of speed and power, gears should conform perfectly to the designed profile and dimensions. Misalignments and gear runout will result in vibrations, chatter, noise, and loss of power. Therefore, one cannot understate the importance of precise measurement and inspection techniques for gears. On the other hand, threaded components should meet stringent quality requirements to satisfy the property of *interchangeability*. Geometric aspects of screw threads are quite complex and, therefore, thread gauging is an integral part of a unified thread gauging system.

The most common forms of gear teeth are involute and cycloidal. The major gear types are spur, helical, bevel, spiral, and worm gears. Coverage of the entire range of inspection methods and instrumentation is an arduous task and requires a separate volume altogether. Therefore, this chapter is confined to the major inspection methods suited for spur gears having an involute

profile. We are sure that the reader will be benefited with this basic knowledge and be motivated to refer to standard books dealing with inspection of gears and screw threads. While the first part of the chapter deals with measurements of gears, the second part outlines some major techniques used for the measurement of screw threads.

Gears used to transmit power, & can change the direction of movement or increase the speed.

8.2 GEAR TERMINOLOGY

Each gear has a unique form or geometry. The gear form is defined by various elements. An illustration of the gear highlighting the important elements is referred to as 'gear terminology'. This section explains the types of gears and their terminology.

8.2.1 Types of Gears

The common types of gears used in engineering practices are described in this section. The information provided here is very brief, and the reader is advised to read a good book on 'theory of machines' to understand the concepts better.

1. **Spur gears** These gears are the simplest of all gears. The gear teeth are cut on the periphery and are parallel to the axis of the gear. They are used to transmit power and motion between parallel shafts (Fig. 8.1).

2. **Helical gears** The gear teeth are cut along the periphery, but at an angle to the axis of the gear. Each tooth has a helical or spiral form. These gears can deliver higher torque since there are more number of teeth in a mesh at any given point of time. They can transmit motion between parallel or non-parallel shafts.

3. **Herringbone gears** These gears have two sets of helical teeth, one right-hand and the other left-hand, machined side by side (Fig. 8.2).

4. **Worm and worm gears** A worm is similar to a screw having single or multiple start threads, which form the teeth of the worm. The worm drives the worm gear or worm wheel to enable transmission of motion. The axes of worm and worm gear are at right angles to each other (Fig. 8.3).



Fig. 8.1 Spur gear



Fig. 8.2 Herringbone gear

* Teams Links :

1 Gears : Types and its applications .



Spur Gear

* teeth are straight & parallel to the axis. (Simple design).
→ slow speed gears.



Helical Gear

→ for heavy load applications.

Teeth inclined to the gear axis in form of (helix).
* high speed gears.



Double Helical Gear (Herringbone Gear)

↳ two helical gears placed side by side.



Bevel Gear

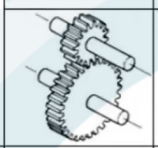
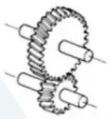
↳ two non-parallel or intersecting



Worm Gear

→ to transmit power.
Worm gears : Screw thread.

one gear has screw thread ⇒ vibration free.

	Spur	Bevel		Worm	Hypoid	Helical
		Straight Bevel	Spiral Bevel			
Type						
Shaft Arrangement	Parallel shaft	Intersecting shaft	Intersecting shaft	Non intersecting, non parallel shaft	Non intersecting, non parallel shaft	Parallel shaft

2 Gear terminology ✓

3 unknown Gear

Method (1) : module size = $\frac{\text{Diameter}}{\#\text{ teeth} + 2}$

$\frac{OD * \cos(\alpha)}{\#\text{ teeth} + 2}$ for helical gear

For example :



30 tooth → $\frac{48}{30+2} = 1.5$.

→ 30 tooth, 1.5 module gear.

another Example ⇒ D = 28.16 , # teeth = 20 → $\frac{28.16}{22} = 1.28$ → not common size.

* $\left(\frac{1\text{ inch}}{25.4\text{ mm}}\right)$, * $\left(DP = \frac{25.4}{\text{module}}\right)$ ← pitch diamel

$\frac{25.4}{1.28} = 19.84$ DP

= 20 DP gear

4:23
25. Dec.

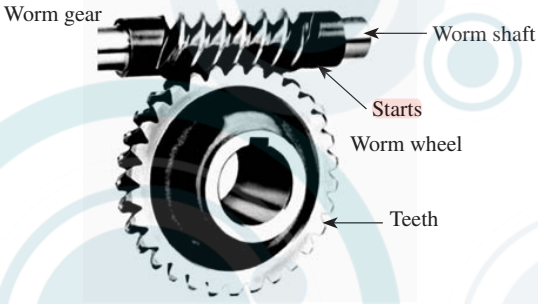


Fig. 8.3 Worm and worm gear



Fig. 8.4 Bevel gears

5. **Bevel gears** These gears are used to connect shafts at any desired angle to each other. The shafts may lie in the same plane or in different planes (Fig. 8.4).

6. **Hypoid gears** These gears are similar to bevel gears, but the axes of the two connecting shafts do not intersect. They carry curved teeth, are stronger than the common types of bevel gears, and are quiet-running. These gears are mainly used in automobile rear axle drives.

A gear tooth is formed by portions of a pair of opposed involutes. By far, the involute tooth profile is most preferred in gears. A clear understanding of the various terminologies associated with gears is extremely important before an attempt is made to learn about inspection and measurement of gears. The following are some of the key terminologies associated with gears, which have been illustrated in Fig. 8.5:

Base circle It is the circle from which the involute form is generated. Only the base circle of a gear is fixed and unalterable.

Outside circle It marks the maximum diameter of the gear up to which the involute form is extended. It is also called the addendum circle. In addition, it is the diameter of the blank from which the gear is cut out.

Pitch circle It is the imaginary circle on which lies the centres of the pitch cylinders of two mating gears.

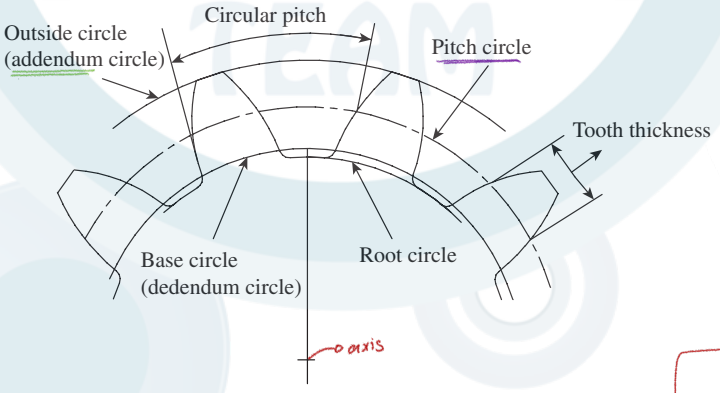
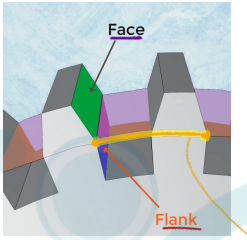


Fig. 8.5 Spur gear terminology

Root circle It is the circle corresponding to the minimum diameter of the gear profile. However, the involute profile is limited only up to the base circle of a spur gear.

Addendum It is the radial distance between the addendum circle and the pitch circle.

Dedendum It is the radial distance between the pitch circle and the root circle.



Face The portion of tooth lying between the addendum circle and the pitch circle is called the face.

Flank The portion of tooth lying between the pitch circle and the dedendum circle is called the flank.

Circular pitch It is the distance between corresponding points of adjacent teeth measured along the pitch circle.

Diametrical pitch It is expressed as the number of teeth per unit diameter of the pitch circle.

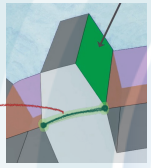
Module It is simply the metric standard for pitch. It is the linear distance (in millimetres) that each tooth of the gear would occupy if the gear teeth were spaced along the pitch diameter. Accordingly, if the pitch circle diameter of the gear is D and the number of teeth is N, then the module m is given by D/N and is expressed in millimetres.

In order to ensure interchangeability and smooth meshing of gears, standard modules are recommended. These standards are also useful for the design of gear cutting tools. The Indian Standards Institute has recommended the following modules (in mm) in order of preference:

First choice 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20

Second choice 1.125, 1.375, 1.75, 2.25, 2.75, 3.5, 4.5, 5.5, 7, 9, 11, 14, 18

Third choice 3.25, 3.75, 6.5



Tooth thickness It is the arc distance measured along the pitch circle from its intercept with one flank to that with the other flank of the same tooth.

Base pitch It is the distance measured around the base circle from the origin of the involute on the tooth to the origin of a similar involute on the next tooth.

Base pitch = Base circumference/Number of teeth

Table 8.1 illustrates the nomenclature of a spur gear.

Table 8.1 Spur gear nomenclature

Nomenclature	Symbol	Formula
Module	m	D/N
Diametrical pitch	DP	$N/D = \pi/p = 1/m$
Pitch	p	$P = \pi m$
Pitch circle diameter	D_p	Nm
Tooth height	h	$2.2m$
Addendum	h'	M
Dedendum	h''	$1.2m$
Outside diameter	D_0	$m(N + 2)$
Root circle diameter	D_r	$D_0 - 4.4m$
Pressure angle	α	20° or 14½°

N = Number of teeth on the gear, D = Outside diameter of the gear.

range of indications obtained with the two-probe check during a complete revolution of the gear is twice the amount resulting from the single-probe check.

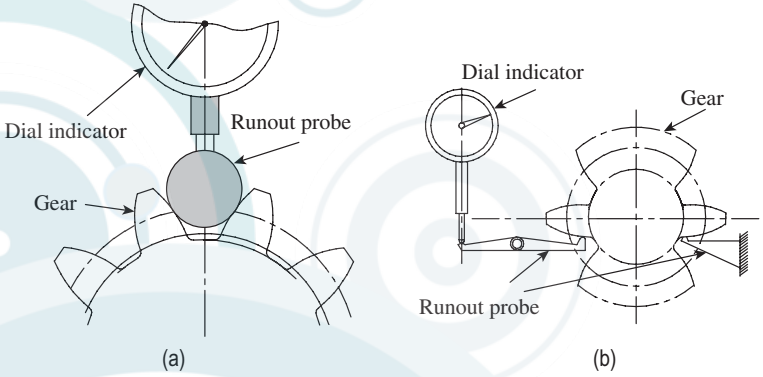


Fig. 8.7 Measurement of radial runout (a) Single-probe check (b) Two-probe check

8.4.2 Measurement of Pitch

Pitch is the distance between corresponding points on equally spaced and adjacent teeth. Pitch error is the difference in distance between equally spaced adjacent teeth and the measured distance between any two adjacent teeth. The two types of instruments that are usually employed for checking pitch are discussed in this section.

Pitch-measuring Instruments

These instruments enable the measurement of chordal pitch between successive pairs of teeth. The instrument comprises a fixed finger and a movable finger, which can be set to two identical points on adjacent teeth along the pitch circle. The pitch variation is displayed on a dial indicator attached to the instrument, as shown in Fig. 8.8. In some cases, the pitch variation is recorded on a chart recorder, which can be used for further measurements. A major limitation of this method is that readings are influenced by profile variations as well as runout of the gear.

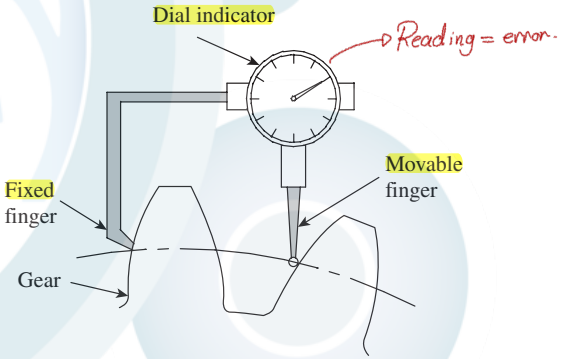


Fig. 8.8 Pitch-measuring instrument

Pitch-checking Instrument

A pitch-checking instrument is essentially a dividing head that can be used to measure pitch variations. The instrument can be used for checking small as well as large gears due to its portability. Figure 8.9 explains the measuring principle for a spur gear. It has two probes—one fixed, called the anvil, and the other movable, called the measuring feeler. The latter is connected to a dial indicator through levers.

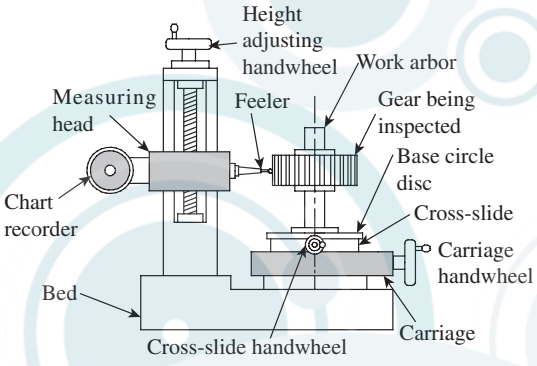


Fig. 8.11 Gear-measuring machine

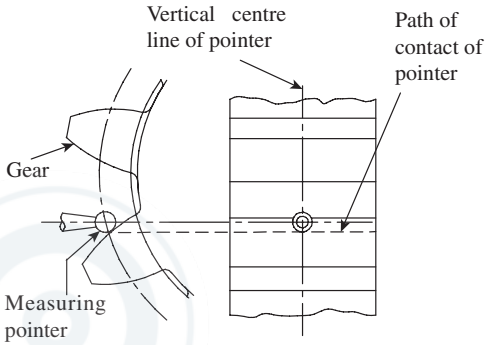


Fig. 8.12 Measurement of lead

feeler can be amplified 250, 500, or 1000 times, the amplification ratio being selected by a selector switch. When there is no error in the involute profile, the trace on the recording chart will be a straight line. Gleason gear inspection machine, a product of Gleason Metrology Systems Corporation, USA, follows the fundamental design aspect of any testing machine with the capability to handle up to 350 mm dia gears. It also integrates certain object-oriented tools to achieve faster cycle times and a better human–machine interaction.

8.4.4 Measurement of Lead

Lead is the axial advance of a helix for one complete rotation about its axis. In case of spur gears, lead tolerance is defined as the allowable deviation across the face width of a tooth surface. Control of lead is necessary in order to ensure adequate contact across the face width when gear and pinion are in mesh. Figure 8.12 illustrates the procedure adopted for checking lead tolerance of a spur gear.

A measuring pointer traces the tooth surface at the pitch circle and parallel to the axis of the gear. The measuring pointer is mounted on a slide, which travels parallel to the centre on which the gear is held. The measuring pointer is connected to a dial gauge or any other suitable comparator, which continuously indicates the deviation. The total deviation shown by the dial indicator over the distance measured indicates the amount of displacement of the gear tooth in the face width traversed.

Measurement of lead is more important in helical and worm gears. Interested readers are advised to refer to a gear handbook to learn more about the same.

8.4.5 Measurement of Backlash

If the two mating gears are produced such that tooth spaces are equal to tooth thicknesses at the reference diameter, then there will not be any clearance in between the teeth that are getting engaged with each other. This is not a practical proposition because the gears will get jammed even from the slightest mounting error or eccentricity of bore to the pitch circle diameter. Therefore, the tooth profile is kept uniformly thinned, as shown in Fig. 8.13. This results in a small play between the mating tooth surfaces, which is called a *backlash*.

We can define backlash as the amount by which a tooth space exceeds the thickness of an

* type of micrometer

is locked using a locking screw. Now, the micrometer is as good as an inspection gauge and can be used to check gears for accuracy of span width. The inspection is carried out with the contact of measuring flanges being made approximately at the mid-working depth of the gear teeth.

Tables that serve as ready reckoners for the span width for given values of module, number of teeth on the gear, and span width are available. Table 8.3 gives a sample of the tabulated values. The advantage of using the table is that the span width can be readily measured without having to calculate the value using relevant equations.

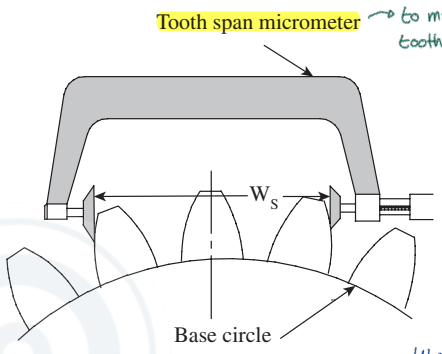


Fig. 8.18 Tooth span micrometer

Table 8.3 Values of span width

Value of base tangent length W_s for uncorrected spur gears in mm Pressure angle = 20° Module m = 1					
Number of teeth on the gear (z)	Number of teeth spanned (s)	Base tangent length (W_s; mm)	Number of teeth on the gear (z)	Number of teeth spanned (s)	Base tangent length (W_s; mm)
7	1	1.5741	25	3	7.7305
8	1	1.5881	26	3	7.7445
9	2	4.5542	27	4	10.7106
10	2	4.5683	28	4	10.7246
11	2	4.5823	29	4	10.7386
–	–		–	–	–
–	–		–	–	–

8.5 COMPOSITE METHOD OF GEAR INSPECTION

Composite action refers to the variation in centre distance when a gear is rolled in tight mesh with a standard gear. It is standard practice to specify composite tolerance, which reflects gear runout, tooth-to-tooth spacing, and profile variations. Composite tolerance is defined as the allowable centre distance variation of the given gear, in tight mesh with a standard gear, for one complete revolution. The Parkinson gear testing machine is generally used to carry out composite gear inspection.

8.5.1 Parkinson Gear Tester

for gear inspection.

It is a popular gear testing machine used in metrology laboratories and tool rooms. The gear being inspected will be made to mesh with a standard gear, and a dial indicator is used to capture radial errors. The features of a Parkinson gear tester are illustrated in Fig. 8.19. The

standard gear is mounted on a fixed frame, while the gear being inspected is fixed to a sliding carriage. The two gears are mounted on mandrels, which facilitate accurate mounting of gears in machines, so that a dial indicator will primarily measure irregularities in the gear under inspection. A dial indicator of high resolution is used to measure the composite error, which reflects errors due to runout, tooth-to-tooth spacing, and profile variations.

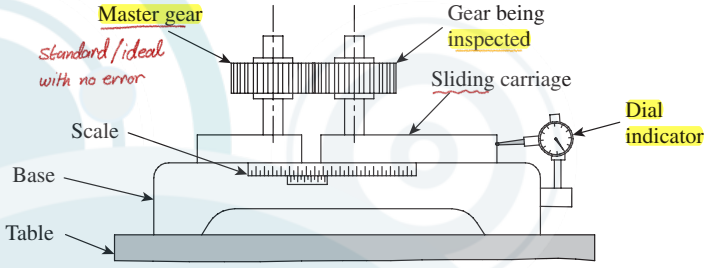


Fig. 8.19 Parkinson gear tester

To start with, the two gears are mounted on respective mandrels and the slide comprising the standard gear is fixed at a convenient position. The sliding carriage is moved along the table, the two gears are brought into mesh, and the sliding carriage base is also locked in its position. Positions of the two mandrels are adjusted in such a way that their axial distance is equal to the gear centre distance as per drawings. However, the sliding carriage is free to slide for a small distance on steel rollers under a light spring force. A vernier scale attached to the machine enables measurement of the centre distance up to 25 μm. The dial indicator is set to zero and the gear under inspection is rotated. Radial variations of the gear being inspected are indicated by the dial indicator. This variation is plotted on a chart or graph sheet, which indicates the radial variations in the gear for one complete rotation.

Many improvisations are possible to the basic machine explained in Section 8.5.1. A waxed paper recorder can be fitted to the machine so that a trace of the variations of a needle in contact with the sliding carriage is made simultaneously. The mechanism can be designed to provide a high degree of magnification.

8.6 MEASUREMENT OF SCREW THREADS

- External
- Internal

Screw thread geometry has evolved since the early 19th century, thanks to the importance of threaded fasteners in machine assemblies. The property of *interchangeability* is associated more strongly with screw threads than with any other machine part. Perhaps, the *Whitworth thread system*, proposed as early as the 1840s, was the first documented screw thread profile that came into use. A couple of decades later, the *Sellers* system of screw threads came into use in the United States. Both these systems were in practice for a long time and laid the foundation for a more comprehensive *unified screw thread system*.

Screw thread gauging plays a vital role in industrial metrology. In contrast to measurements of geometric features such as length and diameter, screw thread measurement is more complex. We need to measure inter-related geometric aspects such as pitch diameter, lead, helix, and flank angle, among others. The following sections introduce screw thread terminology and

discuss the measurements of screw thread elements and thread gauging, which speeds up the inspection process.

8.7 SCREW THREAD TERMINOLOGY

Figure 8.20 illustrates the various terminologies associated with screw threads.

Screw thread The American Society of Tool and Manufacturing Engineers (ASTME) defines a screw thread as follows: screw thread is the helical ridge produced by forming a continuous helical groove of uniform section on the external or internal surface of a cylinder or cone.

Form of thread This is the shape of the contour of one complete thread, as seen in an axial section. Some of the popular thread forms are British Standard Whitworth, American Standard, British Association, Knuckle, Buttress, Unified, Acme, etc.

External thread The screw thread formed on the external surface of a workpiece is called an external thread. Examples of this include bolts and studs.

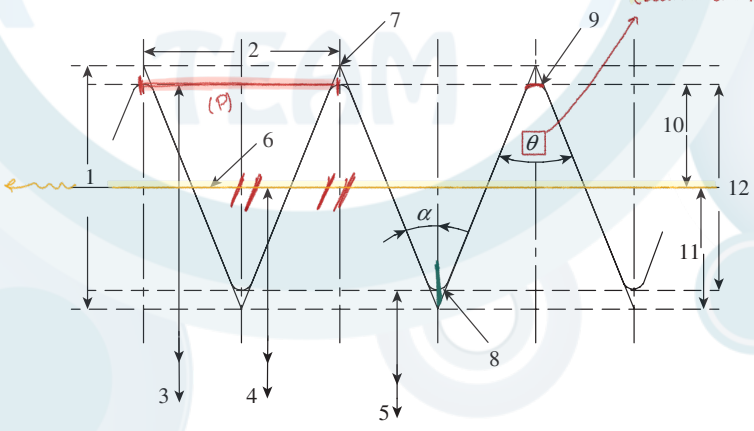
Internal thread The screw thread formed on the internal surface of a workpiece is called an internal thread. The best example for this is the thread on a nut.

Axis of thread (pitch line) This is the imaginary line running longitudinally through the centre of the screw.

Fundamental triangle It is the imaginary triangle that is formed when the flanks are extended till they meet each other to form an apex or a vertex.

Angle of thread This is the angle between the flanks of a thread measured in the axial plane. It is also called an included angle.

Flank angle It is the angle formed between a flank of the thread and the perpendicular to the axis of the thread that passes through the vertex of the fundamental triangle.



Legend
1: Angular pitch
2: Pitch
3: Major diameter
4: Pitch diameter
5: Minor diameter
6: Pitch line
7: Apex
8: Root
9: Crest
10: Addendum
11: Dedendum
12: Depth of thread
θ : Angle of thread
α : Flank angle

Fig. 8.20 Screw thread terminology

Pitch It is the distance between two corresponding points on adjacent threads, measured parallel to the axis of the thread.

Lead It is the axial distance moved by the screw when the crew is given one complete revolution about its axis.

Lead angle It is the angle made by the helix of the thread at the pitch line with the plane perpendicular to the axis.

Helix angle It is the angle made by the helix of the thread at the pitch line with the axis. This angle is measured in an axial plane.

Dia., the surface of it goes through all the crest in External & All root in internal

Major diameter In case of external threads, the major diameter is the diameter of the major cylinder (imaginary), which is coaxial with the screw and touches the crests of an external thread. For internal threads, it is the diameter of the cylinder that touches the root of the threads.

Dia. of imaginary cylinder, the surface goes through all root in the External & All crest in the internal

Minor diameter In case of external threads, the minor diameter is the diameter of the minor cylinder (imaginary), which is coaxial with the screw and touches the roots of an external thread. For internal threads, it is the diameter of the cylinder that touches the crests of the threads. It is also called the root diameter.

radial Distance from the effective dia. to the crest in the External thread.
[From the effective to the crest] in Both.

Addendum It is the radial distance between the major diameter and pitch line for external threads. On the other hand, it is the radial distance between the minor diameter and pitch line for internal threads.

radial destance from the effective to the root in the External
[From the effective to the Root] in Both.

Dedendum It is the radial distance between the minor diameter and pitch line for external threads. On the other hand, it is the radial distance between the major diameter and pitch line for internal threads.

between the major & minor diameter., for imaginary cylinder goes through the material & the emptiness equally.

Effective diameter or pitch diameter It is the diameter of the pitch cylinder, which is coaxial with the axis of the screw and intersects the flanks of the threads in such a way as to make the widths of threads and the widths of spaces between them equal. In general, each of the screw threads is specified by an effective diameter as it decides the quality of fit between the screw and a nut.

Single-start thread In case of a single-start thread, the lead is equal to the pitch. Therefore, the axial distance moved by the screw equals the pitch of the thread.

Multiple-start thread In a multiple-start thread, the lead is an integral multiple of the pitch. Accordingly, a double start will move by an amount equal to two pitch lengths for one complete revolution of the screw.

8.8 MEASUREMENT OF SCREW THREAD ELEMENTS

Measurement of screw thread elements is necessary not only for manufactured components, but also for threading tools, taps, threading hobs, etc. The following sections discuss the methods for measuring major diameter, minor diameter, effective diameter, pitch, angle, and form of threads.

8.8.1 Measurement of Major Diameter

The simplest way of measuring a major diameter is to measure it using a screw thread micrometer. While taking readings, only light pressure must be used, as the anvils make contact with the screw solely at points and any excess application of pressure may result in a slight deformation of anvil due to compressive force, resulting in an error in the measurement. However, for a more precise measurement, it is recommended to use a bench micrometer shown in Fig. 8.21.

A major advantage of a bench micrometer is that a fiducial indicator is a part of the measuring system. It is thus possible to apply a pressure already decided upon by referring to the fiducial indicator. However, there is no provision for holding the workpiece between the centres, unlike a floating carriage micrometer. The inspector has to hold the workpiece by hand while the readings are being taken.

The machine is essentially used as a comparator. To start with, the anvil positions are set by inserting a setting cylinder. A setting cylinder serves as a gauge and has a diameter that equals the OD of the screw thread being inspected. Now, the setting cylinder is taken out, the workpiece is inserted between the anvils, and the deviation is noted down on the micrometer head. Since the position of the fixed anvil will remain unaltered due to the setting of the fiducial arrangement, the movable anvil will shift axially depending on the variation in the value of OD of the screw being inspected. In order to sense deviations on either side of the preset value, the movable anvil will always be set to a position, which can detect small movements in either direction. The error, as measured by the micrometer head, is added to or subtracted from, as the case may be, the diameter of the setting cylinder to get the actual value of OD.

Measurement of the OD of internal threads is trickier, as it is cumbersome to take measurements using conventional instruments. An easier option is to employ some indirect measurement techniques. A cast of the thread is made, which results in a male counterpart of the internal thread. Now, the measurement can be carried out using techniques used for external threads. The cast may be made of plaster of Paris or wax.

8.8.2 Measurement of Minor Diameter

The best way of measuring a minor diameter is to measure it using a floating carriage micrometer described in Chapter 4. The carriage has a micrometer with a fixed spindle on one side and a movable spindle with a micrometer on the other side. The carriage moves on a finely ground 'V' guideway or an anti-friction guideway to facilitate movement in a direction parallel to the axis of the plug gauge mounted between centres.

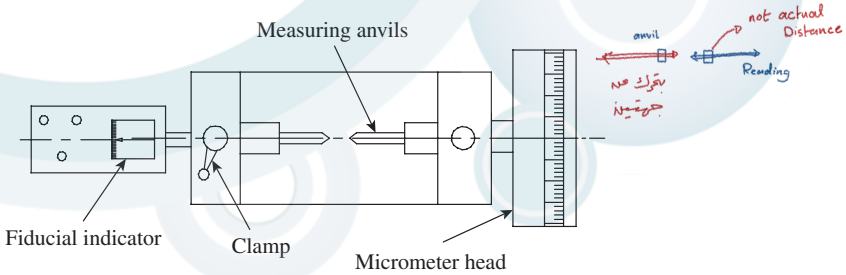
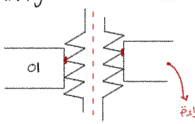


Fig. 8.21 Bench micrometer

* major diameter :



* with known diameter of the cylinder (Dc) then take reading to the cylinder (Rc).

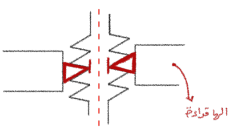
→ Error = Rc - Dc → Rc - Dc = RTh - DTh.

→ Error = RTh - DTh. (DTh unknown)

Example : Dc = 10 mm , Rc = 11mm , RTh = 13mm

DTh = -(Rc - Dc) + RTh = -(1) + 13 = 12 mm.

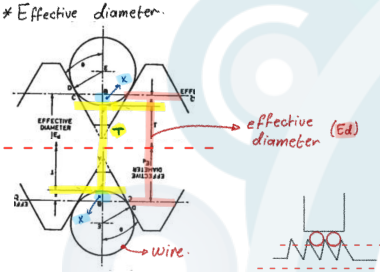
* minor diameter.



* used with prisms. (accessory used with the Bench micrometer).

$R_{th\,(prism)} - D_{th\,minor} = R_{c\,prism} - D_{c\,prism}$

* Effective diameter.



* between the major & minor :

* Distance between the wires (T).

$R_{th\,(wire)} - T = R_{c\,(wire)} - D_c$ --(1)

$2x = \frac{P}{2\tan\theta} - d\left(\frac{1}{\sin\theta} - 1\right)$ --(2)

$D_E = T + 2x$.

* The reading in the micrometer is not the actual Dimension.

1. To find **the major diameter** of the external thread

D_c: diameter of cylinder (known)

R_c: reading of micrometer over the cylinder (measured value)

D_{th}: diameter of the thread (unknown)

R_{th}: reading of micrometer over the thread (measured value)

$(R_{th} - D_{th} = R_c - D_c)$ or $(R_{th} - R_c = D_{th} - D_c)$

After rearrange the formula

$\therefore majorD_{th} = D_c + (R_{th} - R_c)$

2. To find the **Minor diameter** of an external thread

$\therefore minorD_{th} = D_c + (R_{th(prism)} - R_{c(prism)})$

3. To find the **effective diameter** E_d of the external thread (using the three wires method)

For the distance T

$T = D_c + (R_{th(wire)} - R_{c(wire)})$

$E_d = T + 2x$

Where $2x = \frac{P}{2}\cot\theta - d(cosec\,\theta - 1)$

$(d: diameter\ of\ the\ wire)$

The proof for $(E_d = T + 2x)$ is

From the Fig-14, $E_d = T + 2x$

In the ΔABC, $AB = BC\cot\theta$

But, $BC = \frac{1}{4}$ pitch $= \frac{1}{4}P$

Therefore, * $AB = \frac{1}{4}P\cot\theta$

In the ΔADE, $AE = DE\cos ec\theta = \frac{d}{2}\cos ec\theta$

Now, $x = AB - AF$ and $AF = AE - EF = AE - d/2$

$\therefore AF = \frac{d}{2}(\cos ec\theta - 1)$

Therefore, $x = \frac{P}{4}\cot\theta - \frac{d}{2}(\cos ec\theta - 1)$

where,

P= Nominal Pitch

D=Wire Diameter

θ= Nominal Flank Angle or semi angle of thread

* crist to crist = Pitch dia.

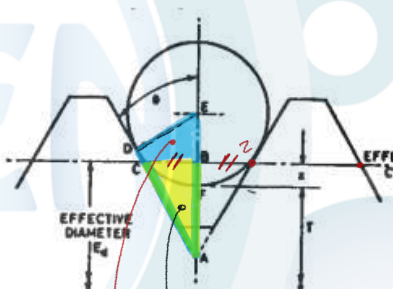


Fig-14 Calculation of simple effective diameter.

BC = Bz = $\frac{1}{4}$ P



$\tan\theta = \frac{BC}{AB} \Rightarrow AB = \frac{BC}{\tan\theta}$.

* $BC = \frac{1}{4}(P)$.

$AB = \frac{P}{4\tan\theta}$ *

* $AF = AE - \frac{1}{2}d$.

$AF = \frac{1}{2}d\left(\frac{1}{\sin} - 1\right)$

* $(X) = AB - AF$

$X = \frac{P}{4\tan\theta} - \frac{d}{2}\left(\frac{1}{\sin\theta} - 1\right)$.

$2x = \frac{P}{2\tan\theta} - d\left(\frac{1}{\sin\theta} - 1\right)$



$\sin\theta = \frac{DE}{AE}$

$AE = \frac{DE}{\sin\theta}$, $DE = \frac{1}{2}(Diameter) = \frac{1}{2}d$.

$AE = \frac{d}{2\sin\theta}$

A. A bench micrometer was used to measure the dimensions for an external thread; the readings are given as:

The reading over the thread =	20.6278 mm
The reading over the cylinder =	20.7166 mm
The reading over the thread (with wires) =	21.0814 mm
The reading over the cylinder (with wires) =	24.2788 mm
The reading over the thread (with prisms) =	22.9336 mm
The reading over the cylinder (with prisms) =	26.5414 mm

And you know that the diameter of the standard cylinder is equal to 20 mm ,the flank angle of the thread $(\theta) = 30^0$, the diameter of the wire $(d) = 2.0207$ mm , and the pitch size of the thread $(p) = 3.5\ mm$

Calculate the major diameter, the minor diameter, and the effective diameter of the thread. (Show your calculations)

[1] $D_{major} = D_c + (R_{th} - R_c)$

$= 20mm + (20.6278 - 20.7166) = 19.9112\ mm.$

[2] $D_{minor} = D_c + (R_{th_{(P)}} - R_{c_{(P)}}) =$

$20mm + (22.9336 - 26.544) = 16.3422\ mm.$

[3] Effective :

① to find $T \Rightarrow T = D_c + (R_{th_{(w)}} - R_{c_{(w)}}) = 20 + (21.0814 - 24.2788)$

$= 16.8026$

② $2x = \frac{P}{2\tan\theta} - d\left(\frac{1}{\sin\theta} - 1\right) = \frac{3.5}{2\tan(30^\circ)} - 2.0207\left(\frac{1}{\sin 30} - 1\right)$

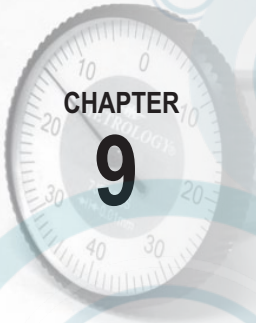
$= 1.0104\ mm$

$D_{eff} = T + 2x = 16.8026 + 1.0104 = 16.813\ mm.$ //

21·Dec

26·Dec

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CHAPTER 9

Metrology of Surface Finish

After studying this chapter, the reader will be able to

- appreciate the importance of surface texture measurement and its significance
- understand the basic reasons for surface irregularities
- explain the terminology associated with the quantification and measurement of surface irregularities
- describe the surface texture characteristics and their symbolic representations
- elucidate the various methods of measurement of surface roughness
- explain the relationship between wavelength of surface roughness, frequency, and cut-off

9.1 INTRODUCTION

In contrast to the concepts we have studied hitherto, surface metrology is basically concerned with deviations between points on the same surface. On the other hand, in all other topics, the fundamental concern has been the relationship between a feature of a part or assembly and some other feature. Even though surface texture is important in many fields of interest such as aesthetics and cosmetics, among others, the primary concern in this chapter pertains to manufactured items that are subject to stress, move in relation to one another, and have close fits joining them. Surface roughness (a term used in a general way here, since it has specific connotations that will be explained shortly) or surface texture depends, to a large extent, on the type of the manufacturing operation. If rough surface for a part is acceptable, one may choose a casting, forging, or rolling operation. In many cases, the surfaces that need to contact each other for some functional requirement have to be machined, possibly followed by a finishing operation like grinding.

The reasons for pursuing surface metrology as a specialized subject are manifold. We would like to make our products operate better, cost less, and look better. In order to achieve these objectives, we need to examine the surfaces of the parts or components more closely, at the microscopic level. It would be naive to assume that two apparently flat contacting surfaces are in perfect contact throughout the apparent area of contact. Most of the earlier laws of friction were based on this assumption (perhaps until 1950). In reality, surfaces have *asperities*, which

refer to the peaks and valleys of surface irregularities. Contact between the mating parts is believed to take place at the peaks. When the parts are forced against each other, they deform either elastically or plastically. In case of elastic behaviour, they return to the full height after deformation by the mating surface. If they behave plastically, some of the deformation is permanent. These aspects have a bearing on the friction characteristics of the parts in contact. As mechanical engineering is primarily concerned with machines and moving parts that are designed to precisely fit with each other, surface metrology has become an important topic in engineering metrology.

Smoth surface. (surface finishing).

9.2 SURFACE METROLOGY CONCEPTS

If one takes a look at the topology of a surface, one can notice that surface irregularities are superimposed on a widely spaced component of surface texture called waviness. Surface irregularities generally have a pattern and are oriented in a particular direction depending on the factors that cause these irregularities in the first place. Figure 9.1 illustrates some of these features.

in metal cutting → new surface
↳ Quality characteristics:
- surface Finish.

*no 100% Flat surface.

error of the form

Secondary waviness

roughness. (primary texture)

Actual form:
sum. of the error of the form
& Secondary texture
& primary texture

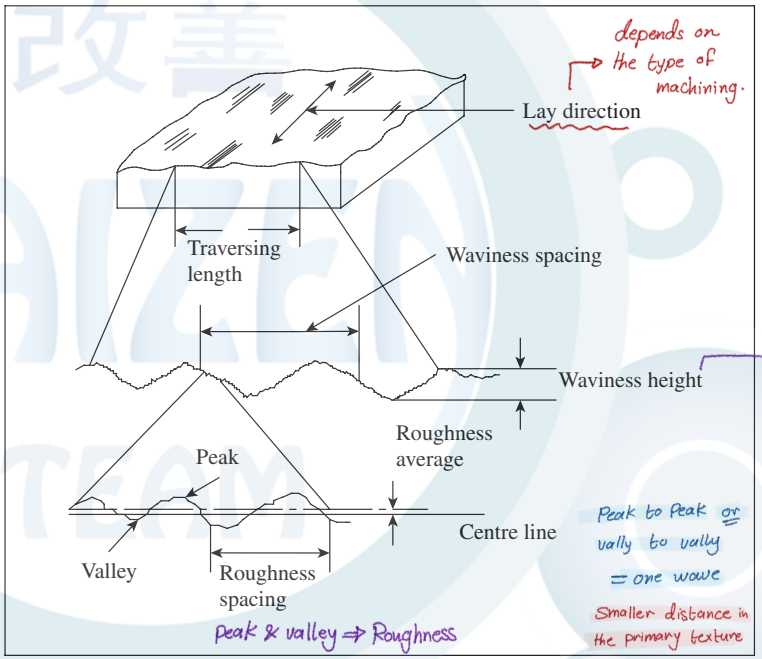


Fig. 9.1 Waviness and roughness

Surface irregularities primarily arise due to the following factors:

1. Feed marks of cutting tools
2. Chatter marks on the workpiece due to vibrations caused during the manufacturing operation
3. Irregularities on the surface due to rupture of workpiece material during the metal cutting operation

4. Surface variations caused by the deformation of workpiece under the action of cutting forces
5. Irregularities in the machine tool itself like lack of straightness of guideways

Thus, it is obvious that it is practically impossible to produce a component that is free from surface irregularities. Imperfections on a surface are in the form of succession of hills and valleys varying in both height and spacing. In order to distinguish one surface from another, we need to quantify surface roughness; for this purpose, parameters such as height and spacing of surface irregularities can be considered. In mechanical engineering applications, we are primarily concerned with the roughness of the surface influenced by a machining process. For example, a surface machined by a single-point cutting tool will have a roughness that is uniformly spaced and directional. In the case of a finish machining, the roughness is irregular and non-directional. In general, if the hills and valleys on a surface are closely packed, the wavelength of the waviness is small and the surface appears rough. On the other hand, if the hills and valleys are relatively far apart, waviness is the predominant parameter of interest and is most likely caused by imperfections in the machine tool. If the hills and valleys are closely packed, the surface is said to have a primary texture, whereas surfaces with pronounced waviness are said to have a secondary texture.

9.3 TERMINOLOGY

Roughness The American Society of Tool and Manufacturing Engineers (ASTME) defines roughness as the finer irregularities in the surface texture, including those irregularities that result from an inherent action of the production process. Roughness spacing is the distance between successive peaks or ridges that constitute the predominant pattern of roughness. Roughness height is the arithmetic average deviation expressed in micrometres and measured perpendicular to the centre line.

Waviness It is the more widely spaced component of surface texture. Roughness may be considered to be superimposed on a wavy surface. Waviness is an error in form due to incorrect geometry of the tool producing the surface. On the other hand, roughness may be caused by problems such as tool chatter or traverse feed marks in a supposedly geometrically perfect machine. The spacing of waviness is the width between successive wave peaks or valleys. Waviness height is the distance from a peak to a valley.

Lay It is the direction of the predominant surface pattern, ordinarily determined by the production process used for manufacturing the component. Symbols are used to represent lays of surface pattern, which will be discussed in Section 9.5.

Defect on the surface.

Flaws These are the irregularities that occur in isolation or infrequently because of specific causes such as scratches, cracks, and blemishes.

Error of the form (wider)
⇓
Waviness (Secondary)
⇓
Roughness (primary)

Surface texture It is generally understood as the repetitive or random deviations from the nominal surface that form the pattern of the surface. Surface texture encompasses roughness, waviness, lay, and flaws.

Errors of form These are the widely spaced repetitive irregularities occurring over the full length of the work surface. Common types of errors of form include bow, snaking, and lobbing.

9.4 ANALYSIS OF SURFACE TRACES

It is required to assign a numerical value to surface roughness in order to measure its degree. This will enable the analyst to assess whether the surface quality meets the functional requirements of a component. Various methodologies are employed to arrive at a representative parameter of surface roughness. Some of these are 10-point height average (Rz), root mean square (RMS) value, and the centre line average height (Ra), which are explained in the following paragraphs.

9.4.1 Ten-point Height Average Value

It is also referred to as the *peak-to-valley height*. In this case, we basically consider the average height encompassing a number of successive peaks and valleys of the asperities. As can be seen in Fig. 9.2, a line AA parallel to the general lay of the trace is drawn. The heights of five consecutive peaks and valleys from the line AA are noted down.

The average peak-to-valley height Rz is given by the following expression:

$$Rz = \frac{(h_1 + h_3 + h_5 + h_7 + h_9) - (h_2 + h_4 + h_6 + h_8 + h_{10})}{5} \times \frac{1000}{\text{Vertical magnification}} \mu m$$

9.4.2 Root Mean Square Value

Until recently, RMS value was a popular choice for quantifying surface roughness; however, this has been superseded by the centre line average value. The RMS value is defined as the square root of the mean of squares of the ordinates of the surface measured from a mean line. Figure 9.3 illustrates the graphical procedure for arriving at an RMS value.

With reference to this figure, if h_1, h_2, ..., h_n are equally spaced ordinates at points 1, 2, ... , n, then

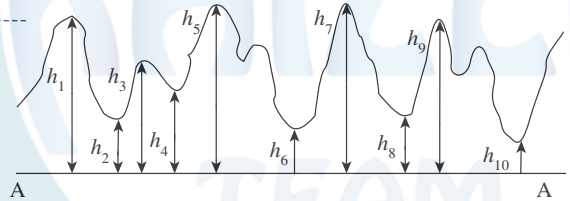


Fig. 9.2 Measurement to calculate the 10-point height average

$$h_{RMS} = \frac{\sqrt{(h_1^2 + h_2^2 + \ldots + h_n^2)}}{n}$$

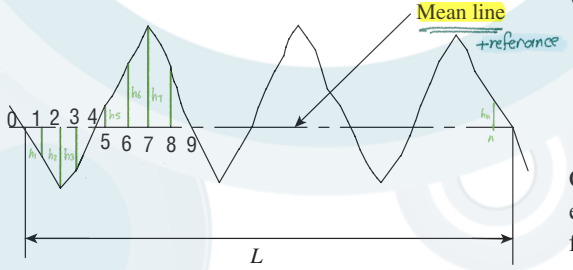


Fig. 9.3 Representation of an RMS value

9.4.3 Centre Line Average Value

The Ra value is the prevalent standard for measuring surface roughness. It is defined as the average height from a mean line of all ordinates of the surface, regardless of sign. With reference to Fig. 9.4, it can be shown that

$$Ra = \frac{A_1 + A_2 + \ldots + A_N}{L}$$

$$= \Sigma A / L$$

Interestingly, four countries (USA, Canada, Switzerland, and Netherlands) have exclusively adopted Ra value as the standard for measuring surface roughness. All other countries have included other assessment methods in addition to the Ra method. For

center line method:
areas ⇒ All (+ve)

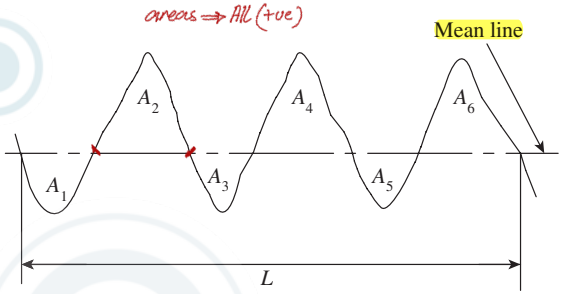


Fig. 9.4 Representation of Ra value

instance, France has seven additional standards.

It should be mentioned here that the Ra value is an index for surface texture comparison and not a dimension. This value is always much less than the peak-to-valley height. It is generally a popular choice as it is easily understood and applied for the purpose of measurement. The bar chart shown in Fig. 9.5 illustrates the typical Ra values obtained in basic manufacturing operations.

Quality of the surface ⇒ depends on the process · ✗ process parameter

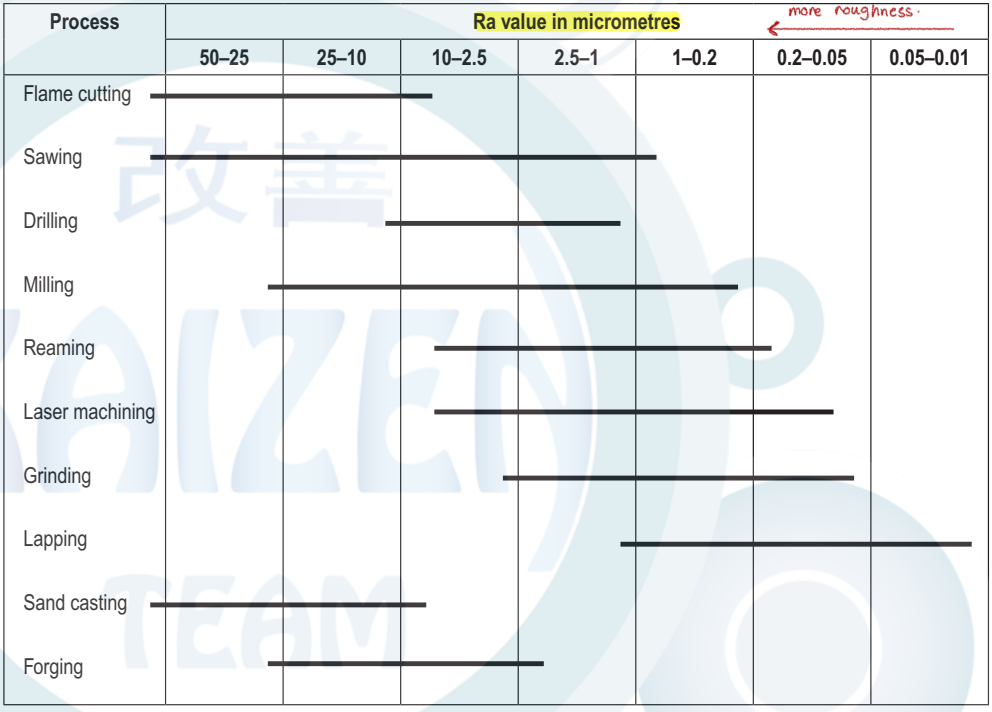


Fig. 9.5 Bar chart indicating the range of Ra values for various manufacturing operations

Note: The bars indicate the entire range. In most cases, the Ra value is restricted to the mid 50% portion of the bars.

9.5 SPECIFICATION OF SURFACE TEXTURE CHARACTERISTICS

Design and production engineers should be familiar with the standards adopted for specification of the characteristics of surface texture. Symbols are used to designate surface irregularities such as the lay of surface pattern and the roughness value. Figure 9.6 illustrates the symbolic

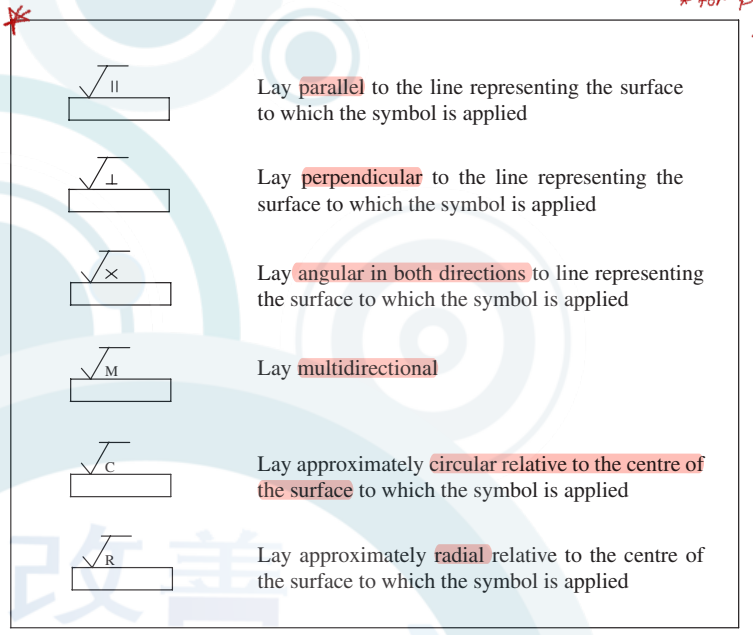


Fig. 9.6 Symbolic representation of the various types of lays of a surface texture

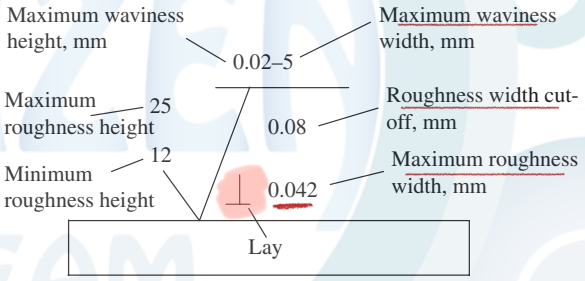


Fig. 9.7 Surface texture symbols

representation of the various types of lays and Fig. 9.7 highlights surface texture symbols with specifications.

9.6 METHODS OF MEASURING SURFACE FINISH

There are basically two approaches for measuring surface finish: comparison and direct measurement. The former is the simpler of the two but is more subjective in nature. The comparative method advocates assessment of surface texture by observation or feel of the surface. Microscopic examination is an obvious improvisation of this method. However, it still

has two major drawbacks. First, the view of a surface may be deceptive; two surfaces that appear identical may be quite different. Second, the height of the asperities cannot be readily determined. Touch is perhaps a better method than visual observation. However, this method is also subjective in nature and depends, to a large extent, on the judgement of a person, and therefore not reliable.

These limitations have driven metrology experts to devise ways and means of directly measuring surface texture by employing direct methods. Direct measurement enables a numerical value to be assigned to the surface finish. The following sections explain the popular methods for the determination of surface texture.

9.7 STYLUS SYSTEM OF MEASUREMENT

The stylus system of measurement is the most popular method to measure surface finish. The operation of stylus instruments is quite similar to a phonograph pickup. A stylus drawn across the surface of the workpiece generates electrical signals that are proportional to the dimensions of the asperities. The output can be generated on a hard copy unit or stored on some magnetizable media. This enables extraction of measurable parameters from the data, which can quantify the degree of surface roughness. The following are the features of a stylus system:

1. A skid or shoe drawn over the workpiece surface such that it follows the general contours of the surface as accurately as possible (the skid also provides the datum for the stylus)
2. A stylus that moves over the surface along with the skid such that its motion is vertical relative to the skid, a property that enables the stylus to capture the contours of surface roughness independent of surface waviness
3. An amplifying device for magnifying the stylus movements
4. A recording device to produce a trace or record of the surface profile
5. A means for analysing the profile thus obtained

9.7.1 Stylus and Datum

There are two types of stylus instruments: true datum and surface datum, which are also known as *skidless* and *skid* type, respectively. In the skidless instrument, the stylus is drawn across the surface by a mechanical movement that results in a precise path. The path is the datum from which the assessment is made. In the skid-type instrument, the stylus pickup unit is supported by a member that rests on the surface and slides along with it. This additional member is the skid or the shoe. Figure 9.8 illustrates the relationship between the stylus and the skid.

Skids are rounded at the bottom and fixed to the pickup unit. They may be located in front of or behind the stylus. Some instruments use a shoe as a supporting slide instead of a skid. Shoes are flat pads with swivel mountings in the head. The datum created by a skid or a shoe is the locus of its centre of curvature as it slides along the surface.

The stylus is typically a diamond having a

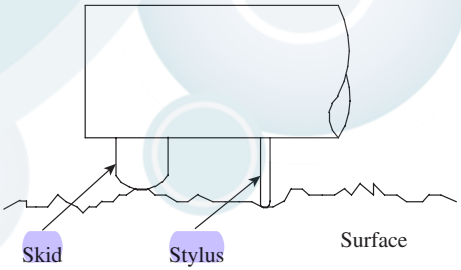
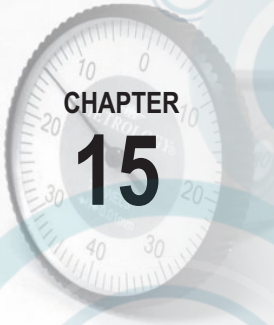


Fig. 9.8 Skid and stylus type

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CHAPTER
15

Measurement of Temperature

After studying this chapter, the reader will be able to

- understand the basics of temperature measurement
- describe the methods of temperature measurements
- explain thermocouples and the different laws of thermocouples
- elucidate the different resistance temperature detectors
- comprehend calibration of liquids in glass thermometers
- discuss bimetallic strip thermometers
- throw light on pyrometers

15.1 INTRODUCTION

We know that temperature is a physical property of a material that gives a measure of the average kinetic energy of the molecular movement in an object or a system. Temperature can be defined as a condition of a body by virtue of which heat is transferred from one system to another. It is pertinent to mention here that both temperature and heat are different. Temperature is a measure of the internal energy of a system, whereas heat is a measure of the transfer of energy from one system to another. Heat transfer takes place from a body at a higher temperature to one at a lower temperature. The two bodies are said to be in thermal equilibrium when both of them are at the same temperature and no heat transfer takes place between them. The rise in temperature of a body is due to greater absorption of heat, which increases the movement of the molecules within the body.

The first thermometer was developed by Galileo Galilei in the 17th century, which has undergone significant improvement with the advancement of science and technology; present-day thermometers are capable of measuring temperatures more accurately and precisely. In 1724, D.G. Fahrenheit, a German physicist, contributed significantly to the development of thermometry. He proposed his own scale, in which 32° and 212° were considered the freezing point and boiling point of water, respectively. The Swedish physicist Anders Celsius, in 1742, developed the mercury-in-glass thermometer. He identified two points, namely the melting point of ice and the boiling point of water, and assigned 0° and 100°, respectively, to them. He made 100 divisions between these two points. In 1859, William John Macquorn Rankine, a Scottish physicist, proposed an absolute or thermodynamic scale, known as Rankine scale

when, after investigating the changes in thermal energy with changes in temperature, he came to a conclusion that the theoretical temperature of each of the substances was the same at zero thermal energy level. According to him, this temperature was approximately equal to –460 °F.

William Thomson, first Baron Kelvin, popularly known as Lord Kelvin, a British physicist, introduced a new concept, known as the Kelvin scale, in the mid-1800s. He suggested 0K as the absolute temperature of gas and 273K as the freezing point of water. A comparison between Kelvin, Celsius, and Fahrenheit scales with respect to absolute zero, and boiling and freezing points of water is shown in Table 15.1. Although human beings generally perceive temperature as hot, warm (neutral), or cold, from an engineering perspective, a precise and accurate measurement of temperature is essential.

Table 15.1 Comparison of temperature scales

Scales	Water boils	Water freezes	Absolute zero
Kelvin	373.16 K	273.16 K	0 K
Celsius	100 °C	0 °C	−273.16°C
Fahrenheit	212 °F	32 °F	−459.7 °F

$\frac{F-32}{212-32} = \frac{C-0}{100-0}$

$\frac{F-32}{180} = \frac{C}{100} \Rightarrow C = \frac{(F-32)100}{180}$

$= (F-32)/1.8$

The scales used to measure temperature can be divided into relative scales [Fahrenheit (°F) and Celsius (°C)] and absolute scales [Rankine (°R) and Kelvin (K)]. The various temperature scales are related as follows:

$F = 1.8C + 32$

$C = (F - 32)/1.8$

$R = F + 460$ → linear

$K = C + 273$ → Linear

15.2 METHODS OF MEASURING TEMPERATURE

Measurement of temperature cannot be accomplished by direct comparison with basic standards such as length and mass. A standardized calibrated device or system is necessary to determine temperature. In order to measure temperature, various primary effects that cause changes in temperature can be used. The temperature may change due to changes in physical or chemical states, electrical property, radiation ability, or physical dimensions. The response of the temperature-sensing device is influenced by any of the following factors:

1. Thermal conductivity and heat capacity of an element
2. Surface area per unit mass of the element
3. Film coefficient of heat transfer
4. Mass velocity of a fluid surrounding the element
5. Thermal conductivity and heat capacity of the fluid surrounding the element

Temperature can be sensed using many devices, which can broadly be classified into two categories: contact- and non-contact-type sensors. In case of contact-type sensors, the object whose temperature is to be measured remains in contact with the sensor. Inference is then drawn on the assessment of temperature either by knowing or by assuming that the object and

the sensor are in thermal equilibrium. Contact-type sensors are classified as follows:

contact type sensors.

1. Thermocouples
2. Resistance temperature detectors (RTDs)
3. Thermistors
4. Liquid-in-glass thermometers
5. Pressure thermometers
6. Bimetallic strip thermometers

In case of non-contact-type sensors, the radiant power of the infrared or optical radiation received by the object or system is measured. Temperature is determined using instruments such as radiation or optical pyrometers. Non-contact-type sensors are categorized as follows:

1. Radiation pyrometers
2. Optical pyrometers
3. Fibre-optic thermometers

15.3 THERMOCOUPLES

contact measuring device.

made from 2 different types of metal (at least).

* When there is heating → the response from the first metal not the same in the second one.

Thermocouples are active sensors employed for the measurement of temperature. The thermoelectric effect is the direct conversion of temperature differences to an electric voltage. In 1821, Thomas Johan Seebeck discovered that when two dissimilar metals are joined together to form two junctions such that one junction (known as the hot junction or the measured junction) is at a higher temperature than the other junction (known as the cold junction or the reference junction), a net emf is generated. This emf, which also establishes the flow of current, can be measured using an instrument connected as shown in Fig. 15.1. The magnitude of emf generated is a function of the junction temperature. It is also dependent on the materials used to form the two junctions. The thermoelectric emf is a result of the combination of two different effects—the Peltier effect and the Thomson effect.

The French physicist Jean Charles Athanase Peltier discovered that if two dissimilar metals are connected to an external circuit in a way such that a current is drawn, the emf may be slightly altered owing to a phenomenon called Peltier effect. A potential difference always exists between two dissimilar metals in contact with each other. This is known as the Peltier effect.

Thomson found out that the emf at a junction undergoes an additional change due to the existence of a temperature gradient along either or both the metals. The Thomson effect states that even in a single metal a potential gradient exists, provided there is a temperature gradient.

Both these effects form the basis of a thermocouple, which finds application in temperature measurement. The flow of current through the circuit is spontaneous when two dissimilar metals are joined together to form a closed circuit, that is, a thermocouple, provided one junction is maintained at a temperature different from the other. This effect is termed the Seebeck effect.

In Fig. 15.1, if temperatures at the hot junction (T_1) and the cold junction (T_2) are equal and at the same time opposite, then there will not be any flow of current. However, if they are unequal, then the emfs will not balance and hence current will flow. It is to be mentioned here that the voltage signal is a function of the junction temperature at the measured end and the voltage increases as the temperature rises. Variations in emf are calibrated in terms of temperatures; the devices employed to record these observations are termed thermocouple pyrometers.

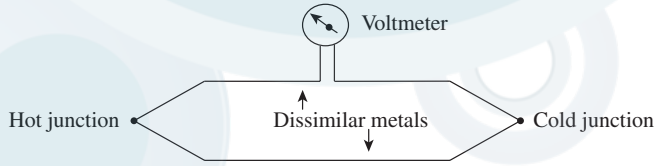


Fig. 15.1 Basic thermocouple circuit

15.3.1 Laws of Thermocouples

Apart from the Peltier and Thomson effects, which form the basis of thermoelectric emf generation, three laws of thermocouples that govern this phenomenon are required to be studied in order to understand their theory and applicability. They also provide some useful information on the measurement of temperature.

Law of Homogeneous Circuit

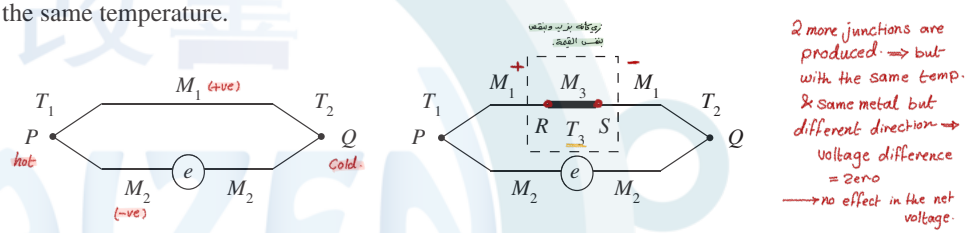
This law states that a thermoelectric current cannot be sustained in a circuit of a single homogenous material, regardless of the variation in its cross section and by the application of heat alone. This law suggests that two dissimilar materials are required for the formation of any thermocouple circuit.

Law of Intermediate Metals

If an intermediate metal is inserted into a thermocouple circuit at any point, the net emf will not be affected provided the two junctions introduced by the third metal are at identical temperatures. This law allows the measurement of the thermoelectric emf by introducing a device into the circuit at any point without affecting the net emf, provided that additional junctions introduced are all at the same temperature.

Junction → point of contact between 2 different types of metal.

(temp-voltage) relationship is non-Linear.
→ will use the tables ,



2 more junctions are produced. ⇒ but with the same temp. & same metal but different direction → voltage difference = zero → no effect in the net voltage.

Fig. 15.2 Law of intermediate metals

It is clear from Fig. 15.2 that when a third metal, M_3, is introduced into the system, two more junctions, R and S, are formed. If these two additional junctions are maintained at the same temperature, say T_3, the net emf of the thermocouple circuit remains unaltered.

Law of Intermediate Temperatures

If a thermocouple circuit generates an emf e_1 when its two junctions are at temperatures T_1 and T_2, and e_2 when the two junctions are at temperatures T_2 and T_3, then the thermocouple will generate an emf of $e_1 + e_2$ when its junction temperatures are maintained at T_1 and T_3 (Fig. 15.3).

This law pertains to the calibration of the thermocouple and is important for providing reference junction compensation. This law allows us to make corrections to the thermocouple readings when the reference junction temperature is different from the temperature at which the thermocouple was calibrated. Usually while preparing the calibration chart of a thermocouple, the reference or cold junction temperature is taken to be equal to 0 °C. However, in practice, the reference junction is seldom maintained at 0 °C; it is usually maintained at ambient conditions. Thus, with the help of the third law, the actual temperature can be determined by means of the calibration chart.

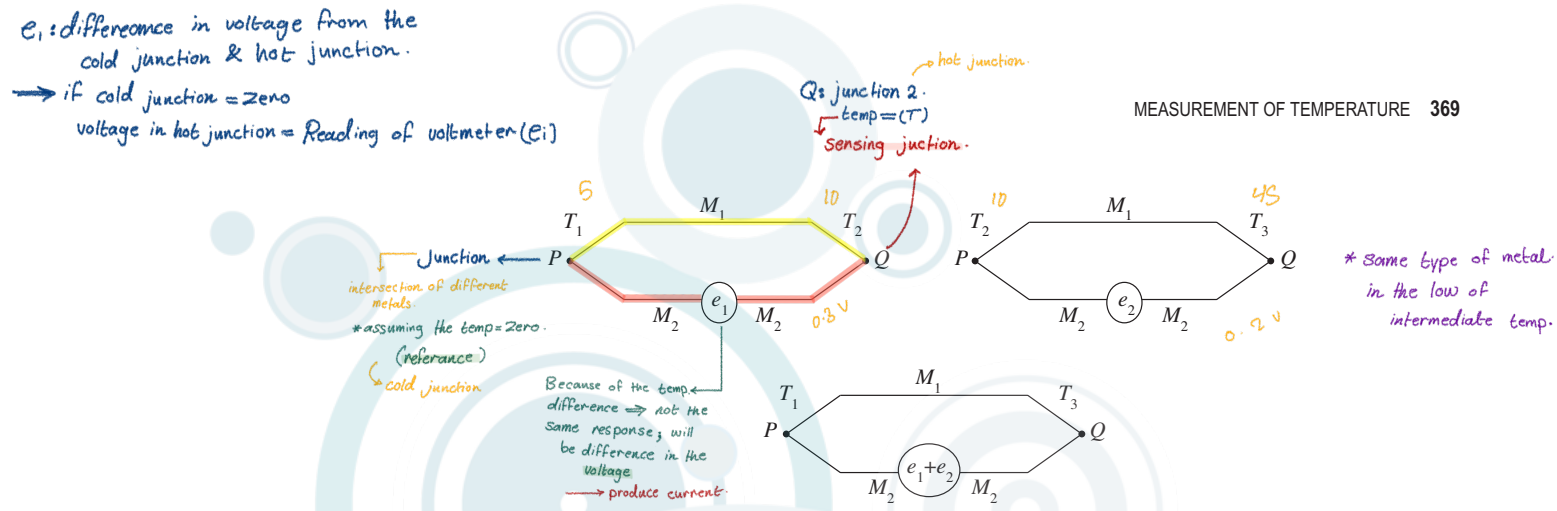


Fig. 15.3 Law of intermediate temperatures

15.3.2 Thermocouple Materials

Theoretically, any two different materials can be used to form a thermocouple. However, only a few are suitable for temperature measurement applications. Combinations of different thermocouple materials and their temperature range are given in Table 15.2. Base metal-type thermocouples like copper–constantan pose high resistance to condensed moisture corrosion. The iron–constantan type is essentially an inexpensive thermocouple capable of enduring oxidizing and reducing atmospheres. The chromel–alumel thermocouple can resist an oxidizing atmosphere.

Table 15.2 Temperature range of various thermocouple materials

Type	Thermocouple materials	Temperature range (°C)
Base metal type		
T	Copper (40%)–constantan (60%)	−200 to 350
J	Iron–constantan	−150 to 750
E	Chromel–constantan (57% Cu, 43% Ni)	−200 to 1000
K	Chromel (90% Ni, 10% Cr)–Alumel (94% Ni, 2% Al, 3% Mn, 1% Si)	−200 to 1300
Rare metal type		
S	Platinum (90%)–rhodium–platinum (10%)	0–1500
R	Platinum–rhodium (87% Pt, 13% Rh)–platinum	0–1500

Thermocouple materials are divided into base metal type and rare, noble, or precious metal type. Platinum (platinum–rhodium) thermocouples are called noble thermocouples, and all other thermocouples belong to the base metal type. In a reducing atmosphere, these thermocouples

TABLE 7 ***Type J Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

J°C

cold junction temp = zero
if cold junction temp ≠ zero
Volt (hot) = Volt (cold) + Reading
Reading of the difference. ex: $V_{(hot)} - V_{(cold)}$.

* First row & First Column (represent temp.)
* values inside the table → difference in voltage assuming temp cold = zero.
* as the temp. increase the diff. in voltage increase

°C	0	1	2	3	4	5	6	7	8	9	10 ** هاد زيادة	°C
					Thermoelectric Voltage in Millivolts							
-210	-8.095											-210
-200	-7.890	-7.912	-7.934	-7.955	-7.976	-7.996	-8.017	-8.037	-8.057	-8.076	-8.095	-200
-190	-7.659	-7.683	-7.707	-7.731	-7.755	-7.778	-7.801	-7.824	-7.846	-7.868	-7.890	-190
-180	-7.403	-7.429	-7.456	-7.482	-7.508	-7.534	-7.559	-7.585	-7.610	-7.634	-7.659	-180
-170	-7.123	-7.152	-7.181	-7.209	-7.237	-7.265	-7.293	-7.321	-7.348	-7.376	-7.403	-170
-160	-6.821	-6.853	-6.883	-6.914	-6.944	-6.975	-7.005	-7.035	-7.064	-7.094	-7.123	-160
-150	-6.500	-6.533	-6.566	-6.598	-6.631	-6.663	-6.695	-6.727	-6.759	-6.790	-6.821	-150
-140	-6.159	-6.194	-6.229	-6.263	-6.298	-6.332	-6.366	-6.400	-6.433	-6.467	-6.500	-140
-130	-5.801	-5.838	-5.874	-5.910	-5.946	-5.982	-6.018	-6.054	-6.089	-6.124	-6.159	-130
-120	-5.426	-5.465	-5.503	-5.541	-5.578	-5.616	-5.653	-5.690	-5.727	-5.764	-5.801	-120
-110	-5.037	-5.076	-5.116	-5.155	-5.194	-5.233	-5.272	-5.311	-5.350	-5.388	-5.426	-110
-100	-4.633	-4.674	-4.714	-4.755	-4.796	-4.836	-4.877	-4.917	-4.957	-4.997	-5.037	-100
-90	-4.215	-4.257	-4.300	-4.342	-4.384	-4.425	-4.467	-4.509	-4.550	-4.591	-4.633	-90
-80	-3.786	-3.829	-3.872	-3.916	-3.959	-4.002	-4.045	-4.088	-4.130	-4.173	-4.215	-80
-70	-3.344	-3.389	-3.434	-3.478	-3.522	-3.566	-3.610	-3.654	-3.698	-3.742	-3.786	-70
-60	-2.893	-2.938	-2.984	-3.029	-3.075	-3.120	-3.165	-3.210	-3.255	-3.300	-3.344	-60
-50	-2.431	-2.478	-2.524	-2.571	-2.617	-2.663	-2.709	-2.755	-2.801	-2.847	-2.893	-50
-40	-1.961	-2.008	-2.055	-2.103	-2.150	-2.197	-2.244	-2.291	-2.338	-2.385	-2.431	-40
-30	-1.482	-1.530	-1.578	-1.626	-1.674	-1.722	-1.770	-1.818	-1.865	-1.913	-1.961	-30
-20	-0.995	-1.044	-1.093	-1.142	-1.190	-1.239	-1.288	-1.336	-1.385	-1.433	-1.482	-20
-10	-0.501	-0.550	-0.600	-0.650	-0.699	-0.749	-0.798	-0.847	-0.896	-0.946	-0.995	-10
0	0.000	-0.050	-0.101	-0.151	-0.201	-0.251	-0.301	-0.351	-0.401	-0.451	-0.501	0
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507	0
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019	10
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537	20
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059	30
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585	40
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116	50
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650	60
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187	70
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726	80
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269	90
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814	100
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360	110
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909	120
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459	130
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010	140
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562	150
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115	160
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669	170
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224	180
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779	190
200	10.779	10.834	10.890	10.945	11.001	11.056	11.112	11.167	11.223	11.278	11.334	200
210	11.334	11.389	11.445	11.501	11.556	11.612	11.667	11.723	11.778	11.834	11.889	210
220	11.889	11.945	12.000	12.056	12.111	12.167	12.222	12.278	12.334	12.389	12.445	220
230	12.445	12.500	12.556	12.611	12.667	12.722	12.778	12.833	12.889	12.944	13.000	230
240	13.000	13.056	13.111	13.167	13.222	13.278	13.333	13.389	13.444	13.500	13.555	240
°C	0	1	2	3	4	5	6	7	8	9	10	°C

pyromation inc

J°C

TABLE 7 ***Type J Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
250	13.555	13.611	13.666	13.722	13.777	13.833	13.888	13.944	13.999	14.055	14.110	250
260	14.110	14.166	14.221	14.277	14.332	14.388	14.443	14.499	14.554	14.609	14.665	260
270	14.665	14.720	14.776	14.831	14.887	14.942	14.998	15.053	15.109	15.164	15.219	270
280	15.219	15.275	15.330	15.386	15.441	15.496	15.552	15.607	15.663	15.718	15.773	280
290	15.773	15.829	15.884	15.940	15.995	16.050	16.106	16.161	16.216	16.272	16.327	290
300	16.327	16.383	16.438	16.493	16.549	16.604	16.659	16.715	16.770	16.825	16.881	300
310	16.881	16.936	16.991	17.046	17.102	17.157	17.212	17.268	17.323	17.378	17.434	310
320	17.434	17.489	17.544	17.599	17.655	17.710	17.765	17.820	17.876	17.931	17.986	320
330	17.986	18.041	18.097	18.152	18.207	18.262	18.318	18.373	18.428	18.483	18.538	330
340	18.538	18.594	18.649	18.704	18.759	18.814	18.870	18.925	18.980	19.035	19.090	340
350	19.090	19.146	19.201	19.256	19.311	19.366	19.422	19.477	19.532	19.587	19.642	350
360	19.642	19.697	19.753	19.808	19.863	19.918	19.973	20.028	20.083	20.139	20.194	360
370	20.194	20.249	20.304	20.359	20.414	20.469	20.525	20.580	20.635	20.690	20.745	370
380	20.745	20.800	20.855	20.911	20.966	21.021	21.076	21.131	21.186	21.241	21.297	380
390	21.297	21.352	21.407	21.462	21.517	21.572	21.627	21.683	21.738	21.793	21.848	390
400	21.848	21.903	21.958	22.014	22.069	22.124	22.179	22.234	22.289	22.345	22.400	400
410	22.400	22.455	22.510	22.565	22.620	22.676	22.731	22.786	22.841	22.896	22.952	410
420	22.952	23.007	23.062	23.117	23.172	23.228	23.283	23.338	23.393	23.449	23.504	420
430	23.504	23.559	23.614	23.670	23.725	23.780	23.835	23.891	23.946	24.001	24.057	430
440	24.057	24.112	24.167	24.223	24.278	24.333	24.389	24.444	24.499	24.555	24.610	440
450	24.610	24.665	24.721	24.776	24.832	24.887	24.943	24.998	25.053	25.109	25.164	450
460	25.164	25.220	25.275	25.331	25.386	25.442	25.497	25.553	25.608	25.664	25.720	460
470	25.720	25.775	25.831	25.886	25.942	25.998	26.053	26.109	26.165	26.220	26.276	470
480	26.276	26.332	26.387	26.443	26.499	26.555	26.610	26.666	26.722	26.778	26.834	480
490	26.834	26.889	26.945	27.001	27.057	27.113	27.169	27.225	27.281	27.337	27.393	490
500	27.393	27.449	27.505	27.561	27.617	27.673	27.729	27.785	27.841	27.897	27.953	500
510	27.953	28.010	28.066	28.122	28.178	28.234	28.291	28.347	28.403	28.460	28.516	510
520	28.516	28.572	28.629	28.685	28.741	28.798	28.854	28.911	28.967	29.024	29.080	520
530	29.080	29.137	29.194	29.250	29.307	29.363	29.420	29.477	29.534	29.590	29.647	530
540	29.647	29.704	29.761	29.818	29.874	29.931	29.988	30.045	30.102	30.159	30.216	540
550	30.216	30.273	30.330	30.387	30.444	30.502	30.559	30.616	30.673	30.730	30.788	550
560	30.788	30.845	30.902	30.960	31.017	31.074	31.132	31.189	31.247	31.304	31.362	560
570	31.362	31.419	31.477	31.535	31.592	31.650	31.708	31.766	31.823	31.881	31.939	570
580	31.939	31.997	32.055	32.113	32.171	32.229	32.287	32.345	32.403	32.461	32.519	580
590	32.519	32.577	32.636	32.694	32.752	32.810	32.869	32.927	32.985	33.044	33.102	590
600	33.102	33.161	33.219	33.278	33.337	33.395	33.454	33.513	33.571	33.630	33.689	600
610	33.689	33.748	33.807	33.866	33.925	33.984	34.043	34.102	34.161	34.220	34.279	610
620	34.279	34.338	34.397	34.457	34.516	34.575	34.635	34.694	34.754	34.813	34.873	620
630	34.873	34.932	34.992	35.051	35.111	35.171	35.230	35.290	35.350	35.410	35.470	630
640	35.470	35.530	35.590	35.650	35.710	35.770	35.830	35.890	35.950	36.010	36.071	640
650	36.071	36.131	36.191	36.252	36.312	36.373	36.433	36.494	36.554	36.615	36.675	650
660	36.675	36.736	36.797	36.858	36.918	36.979	37.040	37.101	37.162	37.223	37.284	660
670	37.284	37.345	37.406	37.467	37.528	37.590	37.651	37.712	37.773	37.835	37.896	670
680	37.896	37.958	38.019	38.081	38.142	38.204	38.265	38.327	38.389	38.450	38.512	680
690	38.512	38.574	38.636	38.698	38.760	38.822	38.884	38.946	39.008	39.070	39.132	690
700	39.132	39.194	39.256	39.318	39.381	39.443	39.505	39.568	39.630	39.693	39.755	700
710	39.755	39.818	39.880	39.943	40.005	40.068	40.131	40.193	40.256	40.319	40.382	710
720	40.382	40.445	40.508	40.570	40.633	40.696	40.759	40.822	40.886	40.949	41.012	720
730	41.012	41.075	41.138	41.201	41.265	41.328	41.391	41.455	41.518	41.581	41.645	730
740	41.645	41.708	41.772	41.835	41.899	41.962	42.026	42.090	42.153	42.217	42.281	740
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 7 ***Type J Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
750	42.281	42.344	42.408	42.472	42.536	42.599	42.663	42.727	42.791	42.855	42.919	750
760	42.919	42.983	43.047	43.111	43.175	43.239	43.303	43.367	43.431	43.495	43.559	760
770	43.559	43.624	43.688	43.752	43.817	43.881	43.945	44.010	44.074	44.139	44.203	770
780	44.203	44.267	44.332	44.396	44.461	44.525	44.590	44.655	44.719	44.784	44.848	780
790	44.848	44.913	44.977	45.042	45.107	45.171	45.236	45.301	45.365	45.430	45.494	790
800	45.494	45.559	45.624	45.688	45.753	45.818	45.882	45.947	46.011	46.076	46.141	800
810	46.141	46.205	46.270	46.334	46.399	46.464	46.528	46.593	46.657	46.722	46.786	810
820	46.786	46.851	46.915	46.980	47.044	47.109	47.173	47.238	47.302	47.367	47.431	820
830	47.431	47.495	47.560	47.624	47.688	47.753	47.817	47.881	47.946	48.010	48.074	830
840	48.074	48.138	48.202	48.267	48.331	48.395	48.459	48.523	48.587	48.651	48.715	840
850	48.715	48.779	48.843	48.907	48.971	49.034	49.098	49.162	49.226	49.290	49.353	850
860	49.353	49.417	49.481	49.544	49.608	49.672	49.735	49.799	49.862	49.926	49.989	860
870	49.989	50.052	50.116	50.179	50.243	50.306	50.369	50.432	50.495	50.559	50.622	870
880	50.622	50.685	50.748	50.811	50.874	50.937	51.000	51.063	51.126	51.188	51.251	880
890	51.251	51.314	51.377	51.439	51.502	51.565	51.627	51.690	51.752	51.815	51.877	890
900	51.877	51.940	52.002	52.064	52.127	52.189	52.251	52.314	52.376	52.438	52.500	900
910	52.500	52.562	52.624	52.686	52.748	52.810	52.872	52.934	52.996	53.057	53.119	910
920	53.119	53.181	53.243	53.304	53.366	53.427	53.489	53.550	53.612	53.673	53.735	920
930	53.735	53.796	53.857	53.919	53.980	54.041	54.102	54.164	54.225	54.286	54.347	930
940	54.347	54.408	54.469	54.530	54.591	54.652	54.713	54.773	54.834	54.895	54.956	940
950	54.956	55.016	55.077	55.138	55.198	55.259	55.319	55.380	55.440	55.501	55.561	950
960	55.561	55.622	55.682	55.742	55.803	55.863	55.923	55.983	56.043	56.104	56.164	960
970	56.164	56.224	56.284	56.344	56.404	56.464	56.524	56.584	56.643	56.703	56.763	970
980	56.763	56.823	56.883	56.942	57.002	57.062	57.121	57.181	57.240	57.300	57.360	980
990	57.360	57.419	57.479	57.538	57.597	57.657	57.716	57.776	57.835	57.894	57.953	990
1000	57.953	58.013	58.072	58.131	58.190	58.249	58.309	58.368	58.427	58.486	58.545	1000
1010	58.545	58.604	58.663	58.722	58.781	58.840	58.899	58.957	59.016	59.075	59.134	1010
1020	59.134	59.193	59.252	59.310	59.369	59.428	59.487	59.545	59.604	59.663	59.721	1020
1030	59.721	59.780	59.838	59.897	59.956	60.014	60.073	60.131	60.190	60.248	60.307	1030
1040	60.307	60.365	60.423	60.482	60.540	60.599	60.657	60.715	60.774	60.832	60.890	1040
1050	60.890	60.949	61.007	61.065	61.123	61.182	61.240	61.298	61.356	61.415	61.473	1050
1060	61.473	61.531	61.589	61.647	61.705	61.763	61.822	61.880	61.938	61.996	62.054	1060
1070	62.054	62.112	62.170	62.228	62.286	62.344	62.402	62.460	62.518	62.576	62.634	1070
1080	62.634	62.692	62.750	62.808	62.866	62.924	62.982	63.040	63.098	63.156	63.214	1080
1090	63.214	63.271	63.329	63.387	63.445	63.503	63.561	63.619	63.677	63.734	63.792	1090
1100	63.792	63.850	63.908	63.966	64.024	64.081	64.139	64.197	64.255	64.313	64.370	1100
1110	64.370	64.428	64.486	64.544	64.602	64.659	64.717	64.775	64.833	64.890	64.948	1110
1120	64.948	65.006	65.064	65.121	65.179	65.237	65.295	65.352	65.410	65.468	65.525	1120
1130	65.525	65.583	65.641	65.699	65.756	65.814	65.872	65.929	65.987	66.045	66.102	1130
1140	66.102	66.160	66.218	66.275	66.333	66.391	66.448	66.506	66.564	66.621	66.679	1140
1150	66.679	66.737	66.794	66.852	66.910	66.967	67.025	67.082	67.140	67.198	67.255	1150
1160	67.255	67.313	67.370	67.428	67.486	67.543	67.601	67.658	67.716	67.773	67.831	1160
1170	67.831	67.888	67.946	68.003	68.061	68.119	68.176	68.234	68.291	68.348	68.406	1170
1180	68.406	68.463	68.521	68.578	68.636	68.693	68.751	68.808	68.865	68.923	68.980	1180
1190	68.980	69.037	69.095	69.152	69.209	69.267	69.324	69.381	69.439	69.496	69.553	1190
1200	69.553											1200

| °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | °C |

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
					Thermoelectric Voltage in Millivolts							
-270	-6.458											-270
-260	-6.411	-6.444	-6.446	-6.448	-6.450	-6.452	-6.453	-6.455	-6.456	-6.457	-6.458	-260
-250	-6.404	-6.408	-6.413	-6.417	-6.421	-6.425	-6.429	-6.432	-6.435	-6.438	-6.441	-250
-240	-6.344	-6.351	-6.358	-6.364	-6.370	-6.377	-6.382	-6.388	-6.393	-6.399	-6.404	-240
-230	-6.262	-6.271	-6.280	-6.289	-6.297	-6.306	-6.314	-6.322	-6.329	-6.337	-6.344	-230
-220	-6.158	-6.170	-6.181	-6.192	-6.202	-6.213	-6.223	-6.233	-6.243	-6.252	-6.262	-220
-210	-6.035	-6.048	-6.061	-6.074	-6.087	-6.099	-6.111	-6.123	-6.135	-6.147	-6.158	-210
-200	-5.891	-5.907	-5.922	-5.936	-5.951	-5.965	-5.980	-5.994	-6.007	-6.021	-6.035	-200
-190	-5.730	-5.747	-5.763	-5.780	-5.797	-5.813	-5.829	-5.845	-5.861	-5.876	-5.891	-190
-180	-5.550	-5.569	-5.588	-5.606	-5.624	-5.642	-5.660	-5.678	-5.695	-5.713	-5.730	-180
-170	-5.354	-5.374	-5.395	-5.415	-5.435	-5.454	-5.474	-5.493	-5.512	-5.531	-5.550	-170
-160	-5.141	-5.163	-5.185	-5.207	-5.228	-5.250	-5.271	-5.292	-5.313	-5.333	-5.354	-160
-150	-4.913	-4.936	-4.960	-4.983	-5.006	-5.029	-5.052	-5.074	-5.097	-5.119	-5.141	-150
-140	-4.669	-4.694	-4.719	-4.744	-4.768	-4.793	-4.817	-4.841	-4.865	-4.889	-4.913	-140
-130	-4.411	-4.437	-4.463	-4.490	-4.516	-4.542	-4.567	-4.593	-4.618	-4.644	-4.669	-130
-120	-4.138	-4.166	-4.194	-4.221	-4.249	-4.276	-4.303	-4.330	-4.357	-4.384	-4.411	-120
-110	-3.852	-3.882	-3.911	-3.939	-3.968	-3.997	-4.025	-4.054	-4.082	-4.110	-4.138	-110
-100	-3.554	-3.584	-3.614	-3.645	-3.675	-3.705	-3.734	-3.764	-3.794	-3.823	-3.852	-100
-90	-3.243	-3.274	-3.306	-3.337	-3.368	-3.400	-3.431	-3.462	-3.492	-3.523	-3.554	-90
-80	-2.920	-2.953	-2.986	-3.018	-3.050	-3.083	-3.115	-3.147	-3.179	-3.211	-3.243	-80
-70	-2.587	-2.620	-2.654	-2.688	-2.721	-2.755	-2.788	-2.821	-2.854	-2.887	-2.920	-70
-60	-2.243	-2.278	-2.312	-2.347	-2.382	-2.416	-2.450	-2.485	-2.519	-2.553	-2.587	-60
-50	-1.889	-1.925	-1.961	-1.996	-2.032	-2.067	-2.103	-2.138	-2.173	-2.208	-2.243	-50
-40	-1.527	-1.564	-1.600	-1.637	-1.673	-1.709	-1.745	-1.782	-1.818	-1.854	-1.889	-40
-30	-1.156	-1.194	-1.231	-1.268	-1.305	-1.343	-1.380	-1.417	-1.453	-1.490	-1.527	-30
-20	-0.778	-0.816	-0.854	-0.892	-0.930	-0.968	-1.006	-1.043	-1.081	-1.119	-1.156	-20
-10	-0.392	-0.431	-0.470	-0.508	-0.547	-0.586	-0.624	-0.663	-0.701	-0.739	-0.778	-10
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540
550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790
800	33.275	33.316	33.357	33.398	33.439	33.480	33.521	33.562	33.603	33.644	33.685	800
810	33.685	33.726	33.767	33.808	33.848	33.889	33.930	33.971	34.012	34.053	34.093	810
820	34.093	34.134	34.175	34.216	34.257	34.297	34.338	34.379	34.420	34.460	34.501	820
830	34.501	34.542	34.582	34.623	34.664	34.704	34.745	34.786	34.826	34.867	34.908	830
840	34.908	34.948	34.989	35.029	35.070	35.110	35.151	35.192	35.232	35.273	35.313	840
850	35.313	35.354	35.394	35.435	35.475	35.516	35.556	35.596	35.637	35.677	35.718	850
860	35.718	35.758	35.798	35.839	35.879	35.920	35.960	36.000	36.041	36.081	36.121	860
870	36.121	36.162	36.202	36.242	36.282	36.323	36.363	36.403	36.443	36.484	36.524	870
880	36.524	36.564	36.604	36.644	36.685	36.725	36.765	36.805	36.845	36.885	36.925	880
890	36.925	36.965	37.006	37.046	37.086	37.126	37.166	37.206	37.246	37.286	37.326	890
900	37.326	37.366	37.406	37.446	37.486	37.526	37.566	37.606	37.646	37.686	37.725	900
910	37.725	37.765	37.805	37.845	37.885	37.925	37.965	38.005	38.044	38.084	38.124	910
920	38.124	38.164	38.204	38.243	38.283	38.323	38.363	38.402	38.442	38.482	38.522	920
930	38.522	38.561	38.601	38.641	38.680	38.720	38.760	38.799	38.839	38.878	38.918	930
940	38.918	38.958	38.997	39.037	39.076	39.116	39.155	39.195	39.235	39.274	39.314	940
950	39.314	39.353	39.393	39.432	39.471	39.511	39.550	39.590	39.629	39.669	39.708	950
960	39.708	39.747	39.787	39.826	39.866	39.905	39.944	39.984	40.023	40.062	40.101	960
970	40.101	40.141	40.180	40.219	40.259	40.298	40.337	40.376	40.415	40.455	40.494	970
980	40.494	40.533	40.572	40.611	40.651	40.690	40.729	40.768	40.807	40.846	40.885	980
990	40.885	40.924	40.963	41.002	41.042	41.081	41.120	41.159	41.198	41.237	41.276	990
1000	41.276	41.315	41.354	41.393	41.431	41.470	41.509	41.548	41.587	41.626	41.665	1000
1010	41.665	41.704	41.743	41.781	41.820	41.859	41.898	41.937	41.976	42.014	42.053	1010
1020	42.053	42.092	42.131	42.169	42.208	42.247	42.286	42.324	42.363	42.402	42.440	1020
1030	42.440	42.479	42.518	42.556	42.595	42.633	42.672	42.711	42.749	42.788	42.826	1030
1040	42.826	42.865	42.903	42.942	42.980	43.019	43.057	43.096	43.134	43.173	43.211	1040
1050	43.211	43.250	43.288	43.327	43.365	43.403	43.442	43.480	43.518	43.557	43.595	1050
1060	43.595	43.633	43.672	43.710	43.748	43.787	43.825	43.863	43.901	43.940	43.978	1060
1070	43.978	44.016	44.054	44.092	44.130	44.169	44.207	44.245	44.283	44.321	44.359	1070
1080	44.359	44.397	44.435	44.473	44.512	44.550	44.588	44.626	44.664	44.702	44.740	1080
1090	44.740	44.778	44.816	44.853	44.891	44.929	44.967	45.005	45.043	45.081	45.119	1090
1100	45.119	45.157	45.194	45.232	45.270	45.308	45.346	45.383	45.421	45.459	45.497	1100
1110	45.497	45.534	45.572	45.610	45.647	45.685	45.723	45.760	45.798	45.836	45.873	1110
1120	45.873	45.911	45.948	45.986	46.024	46.061	46.099	46.136	46.174	46.211	46.249	1120
1130	46.249	46.286	46.324	46.361	46.398	46.436	46.473	46.511	46.548	46.585	46.623	1130
1140	46.623	46.660	46.697	46.735	46.772	46.809	46.847	46.884	46.921	46.958	46.995	1140
1150	46.995	47.033	47.070	47.107	47.144	47.181	47.218	47.256	47.293	47.330	47.367	1150
1160	47.367	47.404	47.441	47.478	47.515	47.552	47.589	47.626	47.663	47.700	47.737	1160
1170	47.737	47.774	47.811	47.848	47.884	47.921	47.958	47.995	48.032	48.069	48.105	1170
1180	48.105	48.142	48.179	48.216	48.252	48.289	48.326	48.363	48.399	48.436	48.473	1180
1190	48.473	48.509	48.546	48.582	48.619	48.656	48.692	48.729	48.765	48.802	48.838	1190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 9 ***Type K Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
					Thermoelectric Voltage in Millivolts							
1200	48.838	48.875	48.911	48.948	48.984	49.021	49.057	49.093	49.130	49.166	49.202	1200
1210	49.202	49.239	49.275	49.311	49.348	49.384	49.420	49.456	49.493	49.529	49.565	1210
1220	49.565	49.601	49.637	49.674	49.710	49.746	49.782	49.818	49.854	49.890	49.926	1220
1230	49.926	49.962	49.998	50.034	50.070	50.106	50.142	50.178	50.214	50.250	50.286	1230
1240	50.286	50.322	50.358	50.393	50.429	50.465	50.501	50.537	50.572	50.608	50.644	1240
1250	50.644	50.680	50.715	50.751	50.787	50.822	50.858	50.894	50.929	50.965	51.000	1250
1260	51.000	51.036	51.071	51.107	51.142	51.178	51.213	51.249	51.284	51.320	51.355	1260
1270	51.355	51.391	51.426	51.461	51.497	51.532	51.567	51.603	51.638	51.673	51.708	1270
1280	51.708	51.744	51.779	51.814	51.849	51.885	51.920	51.955	51.990	52.025	52.060	1280
1290	52.060	52.095	52.130	52.165	52.200	52.235	52.270	52.305	52.340	52.375	52.410	1290
1300	52.410	52.445	52.480	52.515	52.550	52.585	52.620	52.654	52.689	52.724	52.759	1300
1310	52.759	52.794	52.828	52.863	52.898	52.932	52.967	53.002	53.037	53.071	53.106	1310
1320	53.106	53.140	53.175	53.210	53.244	53.279	53.313	53.348	53.382	53.417	53.451	1320
1330	53.451	53.486	53.520	53.555	53.589	53.623	53.658	53.692	53.727	53.761	53.795	1330
1340	53.795	53.830	53.864	53.898	53.932	53.967	54.001	54.035	54.069	54.104	54.138	1340
1350	54.138	54.172	54.206	54.240	54.274	54.308	54.343	54.377	54.411	54.445	54.479	1350
1360	54.479	54.513	54.547	54.581	54.615	54.649	54.683	54.717	54.751	54.785	54.819	1360
1370	54.819	54.852	54.886									1370

°C	0	1	2	3	4	5	6	7	8	9	10	°C

pyromation INC

T°C

TABLE 17 ***Type T Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

°C	0	1	2	3	4	5	6	7	8	9	10	°C
					Thermoelectric Voltage in Millivolts							
-270	-6.258											-270
-260	-6.232	-6.236	-6.239	-6.242	-6.245	-6.248	-6.251	-6.253	-6.255	-6.256	-6.258	-260
-250	-6.180	-6.187	-6.193	-6.198	-6.204	-6.209	-6.214	-6.219	-6.223	-6.228	-6.232	-250
-240	-6.105	-6.114	-6.122	-6.130	-6.138	-6.146	-6.153	-6.160	-6.167	-6.174	-6.180	-240
-230	-6.007	-6.017	-6.028	-6.038	-6.049	-6.059	-6.068	-6.078	-6.087	-6.096	-6.105	-230
-220	-5.888	-5.901	-5.914	-5.926	-5.938	-5.950	-5.962	-5.973	-5.985	-5.996	-6.007	-220
-210	-5.753	-5.767	-5.782	-5.795	-5.809	-5.823	-5.836	-5.850	-5.863	-5.876	-5.888	-210
-200	-5.603	-5.619	-5.634	-5.650	-5.665	-5.680	-5.695	-5.710	-5.724	-5.739	-5.753	-200
-190	-5.439	-5.456	-5.473	-5.489	-5.506	-5.523	-5.539	-5.555	-5.571	-5.587	-5.603	-190
-180	-5.261	-5.279	-5.297	-5.316	-5.334	-5.351	-5.369	-5.387	-5.404	-5.421	-5.439	-180
-170	-5.070	-5.089	-5.109	-5.128	-5.148	-5.167	-5.186	-5.205	-5.224	-5.242	-5.261	-170
-160	-4.865	-4.886	-4.907	-4.928	-4.949	-4.969	-4.989	-5.010	-5.030	-5.050	-5.070	-160
-150	-4.648	-4.671	-4.693	-4.715	-4.737	-4.759	-4.780	-4.802	-4.823	-4.844	-4.865	-150
-140	-4.419	-4.443	-4.466	-4.489	-4.512	-4.535	-4.558	-4.581	-4.604	-4.626	-4.648	-140
-130	-4.177	-4.202	-4.226	-4.251	-4.275	-4.300	-4.324	-4.348	-4.372	-4.395	-4.419	-130
-120	-3.923	-3.949	-3.975	-4.000	-4.026	-4.052	-4.077	-4.102	-4.127	-4.152	-4.177	-120
-110	-3.657	-3.684	-3.711	-3.738	-3.765	-3.791	-3.818	-3.844	-3.871	-3.897	-3.923	-110
-100	-3.379	-3.407	-3.435	-3.463	-3.491	-3.519	-3.547	-3.574	-3.602	-3.629	-3.657	-100
-90	-3.089	-3.118	-3.148	-3.177	-3.206	-3.235	-3.264	-3.293	-3.322	-3.350	-3.379	-90
-80	-2.788	-2.818	-2.849	-2.879	-2.910	-2.940	-2.970	-3.000	-3.030	-3.059	-3.089	-80
-70	-2.476	-2.507	-2.539	-2.571	-2.602	-2.633	-2.664	-2.695	-2.726	-2.757	-2.788	-70
-60	-2.153	-2.186	-2.218	-2.251	-2.283	-2.316	-2.348	-2.380	-2.412	-2.444	-2.476	-60
-50	-1.819	-1.853	-1.887	-1.920	-1.954	-1.987	-2.021	-2.054	-2.087	-2.120	-2.153	-50
-40	-1.475	-1.510	-1.545	-1.579	-1.614	-1.648	-1.683	-1.717	-1.751	-1.785	-1.819	-40
-30	-1.121	-1.157	-1.192	-1.228	-1.264	-1.299	-1.335	-1.370	-1.405	-1.440	-1.475	-30
-20	-0.757	-0.794	-0.830	-0.867	-0.904	-0.940	-0.976	-1.013	-1.049	-1.085	-1.121	-20
-10	-0.383	-0.421	-0.459	-0.496	-0.534	-0.571	-0.608	-0.646	-0.683	-0.720	-0.757	-10
0	0.000	-0.039	-0.077	-0.116	-0.154	-0.193	-0.231	-0.269	-0.307	-0.345	-0.383	0
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.352	0.391	0
10	0.391	0.431	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.790	10
20	0.790	0.830	0.870	0.911	0.951	0.992	1.033	1.074	1.114	1.155	1.196	20
30	1.196	1.238	1.279	1.320	1.362	1.403	1.445	1.486	1.528	1.570	1.612	30
40	1.612	1.654	1.696	1.738	1.780	1.823	1.865	1.908	1.950	1.993	2.036	40
50	2.036	2.079	2.122	2.165	2.208	2.251	2.294	2.338	2.381	2.425	2.468	50
60	2.468	2.512	2.556	2.600	2.643	2.687	2.732	2.776	2.820	2.864	2.909	60
70	2.909	2.953	2.998	3.043	3.087	3.132	3.177	3.222	3.267	3.312	3.358	70
80	3.358	3.403	3.448	3.494	3.539	3.585	3.631	3.677	3.722	3.768	3.814	80
90	3.814	3.860	3.907	3.953	3.999	4.046	4.092	4.138	4.185	4.232	4.279	90
100	4.279	4.325	4.372	4.419	4.466	4.513	4.561	4.608	4.655	4.702	4.750	100
110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228	110
120	5.228	5.277	5.325	5.373	5.422	5.470	5.519	5.567	5.616	5.665	5.714	120
130	5.714	5.763	5.812	5.861	5.910	5.959	6.008	6.057	6.107	6.156	6.206	130
140	6.206	6.255	6.305	6.355	6.404	6.454	6.504	6.554	6.604	6.654	6.704	140
150	6.704	6.754	6.805	6.855	6.905	6.956	7.006	7.057	7.107	7.158	7.209	150
160	7.209	7.260	7.310	7.361	7.412	7.463	7.515	7.566	7.617	7.668	7.720	160
170	7.720	7.771	7.823	7.874	7.926	7.977	8.029	8.081	8.133	8.185	8.237	170
180	8.237	8.289	8.341	8.393	8.445	8.497	8.550	8.602	8.654	8.707	8.759	180
190	8.759	8.812	8.865	8.917	8.970	9.023	9.076	9.129	9.182	9.235	9.288	190
°C	0	1	2	3	4	5	6	7	8	9	10	°C

TABLE 17 ***Type T Thermocouple*** *— thermoelectric voltage as a function of temperature (°C); reference junctions at 0 °C*

Example
1. temp = 306
Difference in voltage = 15.211 mv.
Reading = 17.339
the temp. in hot junction = 342 C°

°C	0	1	2	3	4	5	6	7	8	9	10	°C
					Thermoelectric Voltage in Millivolts							
200	9.288	9.341	9.395	9.448	9.501	9.555	9.608	9.662	9.715	9.769	9.822	200
210	9.822	9.876	9.930	9.984	10.038	10.092	10.146	10.200	10.254	10.308	10.362	210
220	10.362	10.417	10.471	10.525	10.580	10.634	10.689	10.743	10.798	10.853	10.907	220
230	10.907	10.962	11.017	11.072	11.127	11.182	11.237	11.292	11.347	11.403	11.458	230
240	11.458	11.513	11.569	11.624	11.680	11.735	11.791	11.846	11.902	11.958	12.013	240
250	12.013	12.069	12.125	12.181	12.237	12.293	12.349	12.405	12.461	12.518	12.574	250
260	12.574	12.630	12.687	12.743	12.799	12.856	12.912	12.969	13.026	13.082	13.139	260
270	13.139	13.196	13.253	13.310	13.366	13.423	13.480	13.537	13.595	13.652	13.709	270
280	13.709	13.766	13.823	13.881	13.938	13.995	14.053	14.110	14.168	14.226	14.283	280
290	14.283	14.341	14.399	14.456	14.514	14.572	14.630	14.688	14.746	14.804	14.862	290
300	14.862	14.920	14.978	15.036	15.095	15.153	15.211	15.270	15.328	15.386	15.445	300
310	15.445	15.503	15.562	15.621	15.679	15.738	15.797	15.856	15.914	15.973	16.032	310
320	16.032	16.091	16.150	16.209	16.268	16.327	16.387	16.446	16.505	16.564	16.624	320
330	16.624	16.683	16.742	16.802	16.861	16.921	16.980	17.040	17.100	17.159	17.219	330
340	17.219	17.279	17.339	17.399	17.458	17.518	17.578	17.638	17.698	17.759	17.819	340
350	17.819	17.879	17.939	17.999	18.060	18.120	18.180	18.241	18.301	18.362	18.422	350
360	18.422	18.483	18.543	18.604	18.665	18.725	18.786	18.847	18.908	18.969	19.030	360
370	19.030	19.091	19.152	19.213	19.274	19.335	19.396	19.457	19.518	19.579	19.641	370
380	19.641	19.702	19.763	19.825	19.886	19.947	20.009	20.070	20.132	20.193	20.255	380
390	20.255	20.317	20.378	20.440	20.502	20.563	20.625	20.687	20.748	20.810	20.872	390
400	20.872											400

°C	0	1	2	3	4	5	6	7	8	9	10	°C

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Problem A

A voltage of 14.82mV is measured with a type J thermocouple with a 0 degree C reference temperature. Find the temperature of the sensing junction.

- (J) table
- $V_{(cold)} = 0°$
- $V_{Reading} = V_{(hot)}$
- Reading = 14.82

272°	273°
13.666	13.722
14.221	14.277
14.776	14.831
15.330	15.386

Cold junction temperature = zero C

Hot junction temperature = ??

14.776 mv	272 C
14.82 mV	T = ??
14.831 mv	273 C

Using interpolation for 14.82 mV , the temperature =272.8 C

Interpolation:

$$\frac{14.831 - 14.776}{14.831 - 14.82} = \frac{273 - 272}{273 - x}$$

$x = 272.8$

*Interpolation → Assuming linear relationship in a small range.

$$\frac{T - 272}{273 - 272} = \frac{14.82 - 14.776}{14.831 - 14.776}$$

T=272.8 ✓

Problem B

A voltage of 3.444 mV is measured with a type J thermocouple with a 25 degree C reference temperature. Find the temperature of the sensing junction.

From the table

At 25 C = the voltage of the cold junction 1.277 mv

Voltage (hot) = Voltage (cold) + Voltage(voltmeter)

Voltage (hot)= 1.277 +3.444 = 4.721 mV

1. cold junction $\neq 0$

$V_{(hot)} = V_{(cold)} + Reading.$

↳ from (J) table with 25°
V = 1.277 mv.

$V_{(hot)} = 1.277 + 3.444 = 4.721$

4.672	89
4.721	T =??
4.726	90

	89°	90°	
	3.596	3.650	60
	4.133	4.187	70
	4.672	4.726	80
	5.215	5.269	90

* interpolation even if the relation is non-linear.

T= 89.907 c

for interpolation :

$$\frac{4.726 - 4.672}{4.726 - 4.721} = \frac{90 - 89}{90 - x}$$

$= 89.907\ C$

are used with protection. Material combinations such as tungsten–tungsten–rhenium, iridium–tungsten, and iridium–iridium–rhodium are called special types of thermocouples and are used for a high temperature range of 1500–2300 °C. For high-temperature measurements, the thermocouple wire should be thicker. However, an increase in the thickness of the wire lowers the time of response of the thermocouple to temperature variations. Depending on the range of temperature that thermocouples can measure, they are designated by a single letter and grouped accordingly. Base metals, which can measure up to 1000 °C, are designated as Type K, Type E, Type T, and Type J. Noble metals, which can measure up to a temperature of 2000 °C, is classified as Type R, Type S, or Type B. Refractory metals are designated as Type C, Type D, or Type G.

The choice of the thermocouple materials is influenced by several factors. Different combinations of thermocouple materials should possess the following characteristics in order to be used for temperature measurement:

1. Capable of producing a reasonable linear temperature–emf relationship
2. Able to generate sufficient thermo-emf per degree temperature change to facilitate detection and measurement
3. Capable of withstanding persistent high temperatures, rapid temperature variations, and the effects of corrosive environments
4. Good sensitivity to record even small temperature variations
5. Very good reproducibility, which enables easy replacement of the thermocouple by a similar one without any need for recalibration
6. Good calibration stability
7. Economical

15.3.3 Advantages and Disadvantages of Thermocouple Materials

The following are some distinct advantages that merit the use of thermocouples:

1. Temperature can be measured over a wide range.
2. Thermocouples are self-powered and do not require any auxiliary power source.
3. A quick and good response can be obtained.
4. The readings obtained are consistent and hence are consistently repeatable.
5. Thermocouples are rugged, and can be employed in harsh and corrosive conditions
6. They are inexpensive.
7. They can be installed easily.

Expensive if it's made from platinum.

However, thermocouples also have certain disadvantages, which are listed as follows:

1. They have low sensitivity when compared to other temperature-measuring devices such as thermistors and RTDs.
2. Calibration is required because of the presence of some non-linearity.
3. Temperature measurement may be inaccurate due to changes in the reference junction temperature; hence thermocouples cannot be employed for precise measurements.
4. For enhancing the life of thermocouples, they should be protected against contamination and have to be chemically inert.

Thermistor
RTD
Thermocouple
more sensitivity.

RTD: Linear
Thermistor: exp.
Thermocouple & non-Linear (tables).

15.3.4 Thermopiles

An extension of thermocouples is known as a thermopile. A thermopile comprises a number

of thermocouples connected in series, wherein the hot junctions are arranged side by side or in a star formation. In such cases, the total output is given by the sum of individual emfs. The advantage of combining thermocouples to form a thermopile is that a much more sensitive element is obtained. For example, a sensitivity of 0.002 °C at 1 mV/°C can be achieved with a chromel–constantan thermopile consisting of 14 thermocouples. If n identical thermocouples are combined to form a thermopile, then the total emf will be n times the output of the single thermocouple.

For special-purpose applications such as measurement of temperature of sheet glass, thermopiles are constructed using a series of semiconductors. For average temperature measurement, thermocouples can be connected in parallel. During the formation of a thermopile, one has to ensure that the hot junctions of the individual thermocouples are properly insulated from one another.

Figures 15.4(a) and 15.4(b) illustrate, respectively, a thermopile having a series connection and one having a star connection.

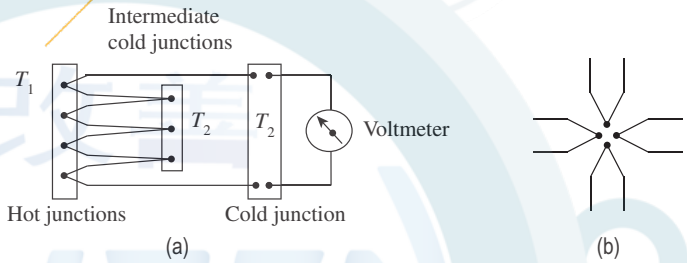


Fig. 15.4 Thermopiles (a) Series connection (b) Star connection

15.4 RESISTANCE TEMPERATURE DETECTORS

Thomas Johan Seebeck, in 1821, discovered thermoelectric emf. In the same year, Sir Humphrey Davy showed that the resistivity of metals is highly dependent on temperature. In 1871, Sir William Siemens proposed the use of platinum as the primary element in resistance thermometers. Platinum is extensively used in high-accuracy resistance thermometers because it is capable of withstanding high temperatures and, at the same time, can sustain excellent stability and exhibit good linearity. The first classical RTD was constructed by C.H. Meyers in 1932, using platinum. A helical coil of platinum was wound on a crossed mica web, and the entire assembly was mounted inside a glass tube. The advantage of this type of construction is that the strain on the wire can be minimized and its resistance can be maximized. Slow thermal response time and fragility of the structure limited its application due to poor thermal contact between platinum and the measured point. Technological advancement led to the development of more rugged RTDs later. The International Practical Temperature Scale was developed in 1968, and pure platinum RTDs have been used as the standard instruments for interpolating between fixed points of the scale. The triple point of water (0.01 °C), boiling point of water (100 °C), triple point of hydrogen (13.81 K), and freezing point of zinc (419.505 °C) are some of the fixed points.

RTDs are also known as resistance thermometers. The American Society for Testing and

Materials has defined the term resistance thermometer as follows: RTD is 'a temperature-measuring device composed of a resistance thermometer element, internal connecting wires, a protective shell with or without means for mounting a connection head, or connecting wire or other fittings, or both'.

We know that the electrical conductivity of a metal is dependent on the movement of electrons through its crystal lattice. An RTD is a temperature sensor that works on the principle that the resistance of electrically conductive materials is proportional to the temperature to which they are exposed. Resistance of a metal increases with an increase in temperature. Hence, metals can be classified as per their positive temperature coefficient (PTC).

When temperature measurement is performed by a resistance thermometer using metallic conductors, it is called a resistance temperature detector (RTD); on the other hand, semiconductors used for temperature measurement are called thermistors.

We know that an RTD measures temperature using the principle that the resistance of a metal changes with temperature. In practice, the RTD element or resistor that is located in proximity to the area where the temperature is to be measured transmits an electrical current. Then, using an instrument, the value of the resistance of the RTD element is measured. Further, on the basis of known resistance characteristics of the RTD element, the value of the resistance is correlated to temperature. RTDs are more rugged and have more or less linear characteristics over a wide temperature range. The range of RTDs is between 200 and 650 °C.

Many materials are commonly used for making resistance thermometers, such as platinum, nickel, and copper, which are contained in a bulb. However, platinum is the most popular and internationally preferred material. When platinum is employed in RTD elements, they are sometimes termed platinum resistance thermometers. The popularity of platinum is due to the following factors:

1. Chemical inertness
2. Almost linear relationship between temperature and resistance
3. Large temperature coefficient of resistance, resulting in readily measurable values of resistance changes due to variations in temperature
4. Greater stability because the temperature resistance remains constant over a long period of time

Selection of a suitable material for RTD elements depends on the following criteria:

1. The material should be ductile so that it can be formed into small wires.
2. It should have a linear temperature-versus-resistance graph.
3. It must resist corrosion.
4. It should be inexpensive.
5. It should possess greater stability and sensitivity.
6. It must have good reproducibility.

RTDs essentially have the following three configurations:

1. A partially supported wound element: A small coil of wire inserted into a hole in a ceramic insulator and attached along one side of that hole
2. Wire-wound RTD: Prepared by winding a platinum or metal wire on a glass or ceramic bobbin and sealed with a coating on molten glass known as wire-wound RTD elements (Fig. 15.5)
3. Thin film RTD: Prepared by depositing or screening a platinum or metal glass slurry film onto a small flat ceramic substrate called thin film RTD elements

Theory:

RTDs are commonly categorized by their nominal resistance at 0 °C. Typical nominal resistance values for platinum thin-film RTDs include 100 and 1000 Ω. In TMT a **PT100 RTD** is used.

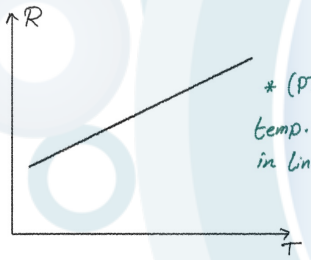
In order to measure temperature with the RTD, you only need to measure the resistance of the RTD, and then substitute the resistance value in the following equation

$$T = \frac{R_o - R}{-0.5(R_o A + \sqrt{R_o^2 A^2 - 4R_o B(R_o - R)})}$$

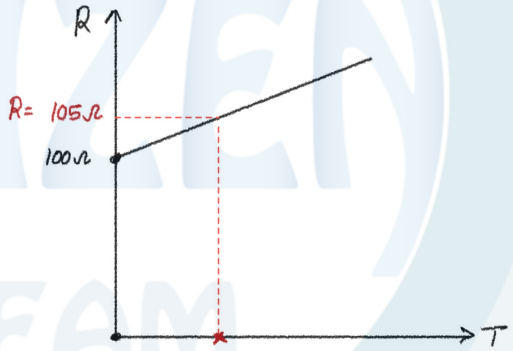
* will give temp. in C°.

Where :

- T : *Calculated temperature in (°C).*
- R_o : *RTD nominal resistance at 0 °C, R_o=100 Ω.* ← depend in type of RTD
- R : *Measured resistance (Ω).*
- Constant depend in the type of metal.
  - $A = 3.90802 \times 10^{-3}$
  - $B = -5.80195 \times 10^{-7}$



* (PTC)
temp. ↑ ⇒ R ↑
in linear relation.



**

$$R = R_o(1 + \alpha \cdot \Delta T)$$

measured ← R
R_o → nominal when temp=zero

α : parameter, depends on the type of material

The general construction of a resistance thermometer is shown in Fig. 15.6. It comprises a number of turns of resistance wire wrapped around a solid silver core. Transmission of heat takes place quickly from the end flange through the core to the winding.

The thin film element used for temperature sensing is manufactured by depositing a very thin (around 10–100 Å) layer of platinum on a ceramic substrate. The platinum layer is coated with epoxy or glass, which protects the deposited platinum film and also acts as a strain reliever for external lead wires. During the early stages of development, thin film sensors were unreliable due to their instability and susceptibility to mechanical failure resulting in the breakage of lead wires. Thin film RTD is the most rugged of the three RTD elements and is preferred for its increased accuracy over time and improved reliability. A thin film responds faster due to its low thermal mass and ease of assembly into smaller packages. Figure 15.7 shows a thin film RTD.

Compared to other types of temperature sensors, RTDs have the following advantages:

1. The resistance versus temperature linearity characteristics of RTDs are higher.
2. They possess greater accuracy (as high as ±0.1 °C). Standard platinum resistance thermometers have ultra-high accuracy of around ±0.0001 °C.
3. They have excellent stability over time.

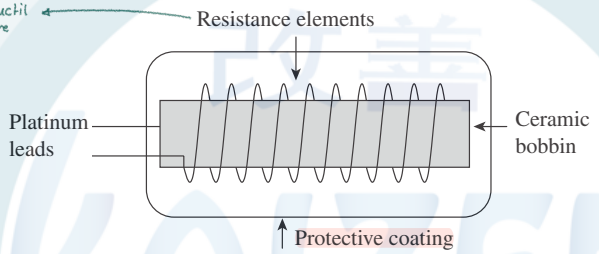


Fig. 15.5 Wire-wound RTD

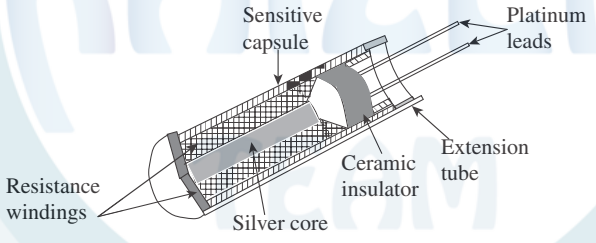


Fig. 15.6 General construction of an RTD

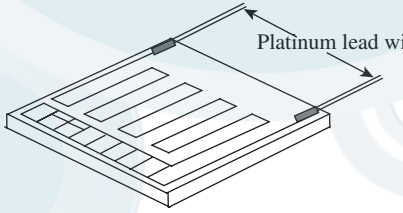


Fig. 15.7 Thin film RTD

4. Resistance elements can be used for the measurement of differential temperature.
5. Temperature-sensitive resistance elements can be replaced easily.
6. RTDs show high flexibility with respect to the choice of measuring equipment, interchangeability of elements, and assembly of components.
7. Multiple resistance elements can be used in an instrument.
8. RTDs have a wide working range without any loss of accuracy and, at the same time, can be employed for small ranges also.
9. They are best suited for remote indication applications.
10. It is possible to operate indicators, recorders, or controllers.

RTDs are also associated with some disadvantages. They are as follows:

1. The use of platinum in RTDs makes them more expensive than other temperature sensors.
2. The nominal resistance is low for a given size, and the change in resistance is much smaller than other temperature sensors.

3. Although its temperature sensitivity is high, it is less than that of thermistors.

15.5 THERMISTORS

Semiconductors that are used to measure temperature are called thermistors. When a thermistor is employed for temperature measurement, its resistance decreases with increase in temperature. The valence electrons, which are mutually shared by the metal atoms, move continuously and freely through the metal during their movement from atom to atom. The vibration in the crystal lattice of atoms increases with the increase in temperature. The free movement of electrons becomes restricted due to an increase in the volume of space occupied by the atoms. In case of thermistors, the valence electrons are attached more firmly to the atoms; some of the electrons are detached and flow due to the increase in temperature, which decreases electrical resistance facilitating the easy flow of electrons. Materials used in thermistors for temperature measurements have very high temperature coefficients (8–10 times higher than platinum and copper) and high resistivity (higher than any pure metal). Thus, they are very sensitive to small variations in temperature and respond very quickly. The relationship between temperature and resistance is given by the following equation:

$$R = R_R e^{\beta\left(\frac{1}{T} - \frac{1}{T_R}\right)}$$

Here, R is the resistance at temperature T, R_R is the resistance at the reference temperature T_R, e is the base of the Napierian logarithm, and β is a constant, which lies in the range of 3000–4600 K depending on the composition.

The temperature coefficient of resistance is given by the following equation:

$$\frac{dR/dT}{R} = \frac{\beta}{T^2}$$

The temperature coefficient of platinum at 25 °C is +0.0036/K and, for thermistors, it is generally around –0.045/K, which is more than 10 times sensitive when compared to platinum. A variety of ceramic semiconductor materials qualify as thermistor materials. Among them, germanium containing precise proportions of arsenic, gallium, or antimony is most preferred. The temperature measurement range of thermistors is –250 to 650 °C.

Thermistors are also produced using oxides of manganese, nickel cobalt, nickel copper, iron, zinc, titanium, and tin. In order to attain better reproducibility and stability of the thermistor characteristics, some chemically stabilizing oxides are added. The oxides are milled into powder form and mixed with a plastic binder, which are then compressed into desired forms such as disks or wafers. Disks are formed by compressing the mixtures using pelleting machines, and the wafers are compression moulded. They are then sintered at high temperatures to produce thermistor bodies. Depending on their intended application, leads are then added to these thermistors and coated if necessary. To achieve the required stability, the thermistors so formed are subjected to a special ageing process. Figure 15.8 illustrates the different forms in which thermistors can be made.

The variation of temperature with voltage and resistance is shown in Fig. 15.9. The use of thermistors as temperature sensors has several advantages:

1. Thermistors possess very high sensitivity, which is much higher than that of RTDs and thermocouples, and hence have the capability to detect very small changes in temperature.

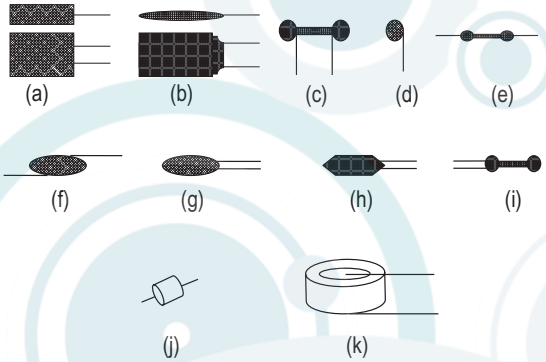


Fig. 15.8 Different forms of thermistors (a, b) Wafers (c–e) Rods (f–i) Beads (j, k) Disks

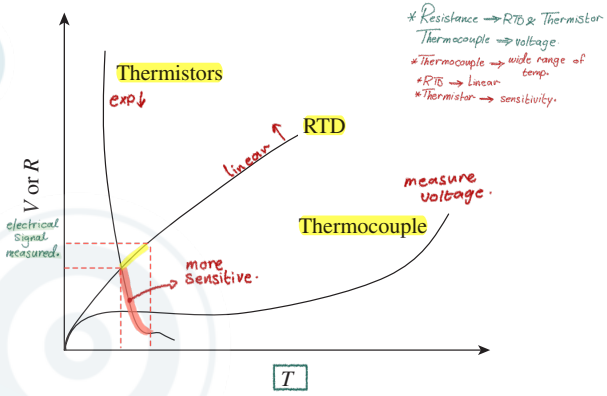


Fig. 15.9 Comparison of temperature characteristics

2. Their response is very fast, and hence, they are employed for precise control of temperature.
3. They are inexpensive.

Thermistors also have certain disadvantages:

1. They have highly non-linear resistance temperature characteristics.
2. The temperature range is narrow.
3. Low fragility is often a problem.
4. High-temperature performance of thermistors is not good and they exhibit instability with time.
5. They are prone to self-heating errors.

15.6 LIQUID-IN-GLASS THERMOMETERS

The liquid-in-glass thermometer is the most popular and is widely used for temperature measurement. It comprises a bulb that contains a temperature-sensing liquid, preferably mercury. Alcohol and pentane, which have lower freezing points than mercury and do not contaminate if the bulb is broken, are also used. Since alcohol has a better expansion coefficient than mercury, it is also used. A graduated capillary tube is connected to the bulb. At the top of the capillary, a safety or expansion bulb is provided. Figure 15.10 shows a liquid-in-glass thermometer. A range cavity is provided just above the bulb to accommodate the range variation. The walls of the bulb should be thin in order to facilitate quick transfer of heat. Further, for the response to be quick, the volume of liquid should be small. However, the larger the volume of the liquid, the higher the sensitivity. Since speed of response depends on the volume of the liquid, a compromise needs to be made between sensitivity and response.

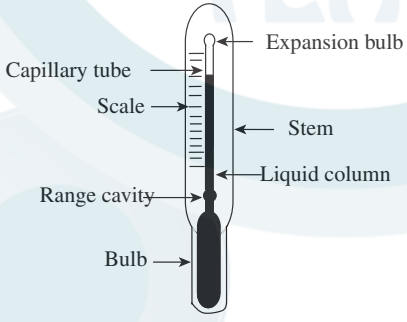


Fig. 15.10 Liquid-in-glass thermometer

The entire assembly is enclosed in a casing to provide protection from breakage. An extra-long stem may be provided to facilitate easy dipping into hot liquids. Calibration of thermometers has to be carried out for better

Theory:

In order to measure temperature with the thermistor, you only need to measure the resistance of the thermistor, and then substitute the resistance value in the following equation

$$T = \frac{1}{a + b(lnR) + c(lnR)^3}$$

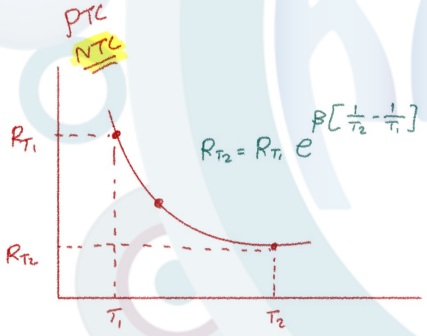
Where :

T : Calculated temperature in (K)
R: Measured resistance in (Ω)
a, b and c are Steinhart-Hart Constants that have the following values

Constant, depend in the type of material.

$a = 1.2407635*10^{-3}$
$b = 2.3612017*10^{-4}$
$c = 8.97975*10^{-8}$

From the above equation you will get the temperature in Kelvin. The value of a, b and c differs from one type of to another.



* Exponential relation.

* non-Linear relationship

* NTC / PTC
  - most used.
  - temp ↑ → R ↓

لازم على الاقل
3 نقاط .

5.15. RESISTANCE THERMOMETERS

The resistance of a conductor changes when its temperature is changed. This property is utilized for measurement of temperature.

The variation of resistance R with temperature T (°K) can be represented by the following relationship for most of the metals as :

$$R = R_0 (1 + \alpha_1 T + \alpha_2 T^2 + ... + \alpha_n T^n + ...) \quad ...(5.55)$$

where R_0 = resistance at temperature $T = 0$ and α_1, α_2, $\alpha_3 ... \alpha_n$ are constants.

The resistance thermometer uses the change in electrical resistance of conductor to determine the temperature.

The resistivity of metals showed a marked dependence on temperature was discovered by Sir Humphry Davy. A few years later Sir William Siemens proferred the use of platinum as an element in the resistance thermometer. His choice proved most propitious, as platinum is used to this day as the primary element in all high accuracy resistance thermometers. In fact, the platinum resistance temperature detector (PRTD) is used today as an interpolation standard from oxygen point (– 182.96°C) to antimony point (630.74°C)

Platinum is especially suited for this purpose, as it can withstand high temperatures while maintaining excellent stability. As a noble metal, it shows limited susceptibility to contamination. All metals produce a positive change in resistance with temperature. This, of course, is the main function of an RTD. The system error is minimized when the nominal value of RTD is large. This implies a metal with a high value of resistivity should be used for RTDs. The lower is the resistivity of the metal, the more material we will have to use.

The requirements of a conductor material to be used in RTDs are :

(*i*) The change in resistance of material per unit change in temperature should be as large as possible.

(*ii*) The material should have a high value of resistivity so that minimum volume of material is used for the construction of RTD.

(*iii*) The resistance of materials should have a continuous and stable relationship with temperature.

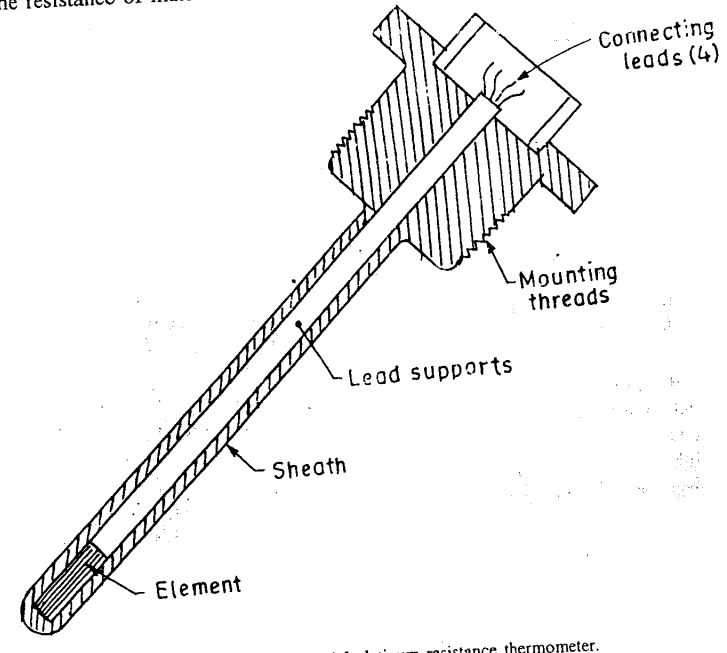


Fig. 5.40. Industrial platinum resistance thermometer.

Gold and **Silver** are rarely used for construction of RTDs on account of their low resistivities. **Tungsten** has relatively a high resistivity, but is reserved for high temperature applications as it is extremely brittle and difficult to work. **Copper** is used occasionally as an RTD element. Its low resistivity forces the element to be longer than the platinum element, but its low linearity and low cost make it an economical alternative. Its upper limit of temperature is about 120°C.

The most common RTDs are made of either platinum, nickel or nickel alloys. The economical **nickel wires** are used over a limited temperature range. They are quite non-linear and tend to drift with time. For measurement integrity, **platinum** is the obvious choice.

The common values of resistance for a platinum RTD range from 10 Ω for the bird cage model to several thousands ohm for the film RTD. The single most common value is 100 Ω at 0°C with a resistance temperature co-efficient of 0.00385/°C. The more chemically pure platinum wire has a resistance temperature co-efficient of 0.00392/°C.

The construction of an industrial type of platinum RTD is shown in Fig. 5.40.

The characteristics of various materials used for resistance thermometers are plotted in Fig. 5.41.

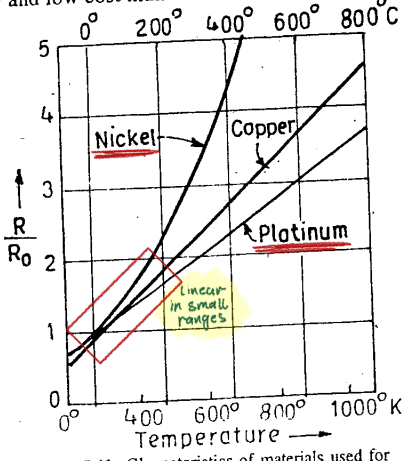


Fig. 5.41. Characteristics of materials used for resistance thermometers.

Metals commonly used for resistance thermometers are listed in Table 5.5 along with their salient properties.

Table 5.5. Metals Used for Resistance Thermometers

Metal	*Resistance temperature Co-efficient /°C* (α)	*Temperature range °C*		*Melting point °C*
		Min	*Max*	
Platinum	0.39	– 260	110	1773
Copper	0.39	0	180	1083
Nickel	0.62	– 220	300	1435
Tungsten	0.45	– 200	1000	3370

An examination of the resistance versus temperature curves of Fig. 5.41, shows that the curves are nearly linear. If fact, when only short temperature spans are considered, the linearity is more evident. This fact is employed to develop approximate analytical equations for resistance versus temperature for a particular metal.

5.15.1. Linear Approximation. A linear approximation means that we may develop an equation for a straight line which approximates the resistance versus temperature curve over a specified span. Fig. 5.42 shows a curve of variation of resistance R with temperature θ°C.

Here a straight line has been drawn between the points of the curve which represent θ_1°C and θ_2°C with θ_0°C representing the mid point temperature. The equation of this straight line is the *linear approximation* of the curve from θ_1°C to θ_2°C. The equation of the straight line is written as :

$$R_\theta = R_{\theta 0} (1 + \alpha_{\theta_0} \Delta\theta) \text{ with } \theta_1 < \theta_0 < \theta_2 \quad ...(5.56)$$

where

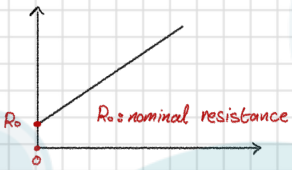
R_θ = approximate resistance at θ°C ; Ω,

R_{θ_0} = approximate resistance at θ_0°C ; Ω,

$\Delta\theta = \theta - \theta_0$ = change in temperature ; °C,

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① RTD: electrical resistance changes with changing the temp. — Linearly, PTC.



* $\frac{R}{R_0} = (1 + \alpha_1(T-T_0) \text{ ---- })$

* the change in resistance can be given by:

$R = R_0(1 + (\alpha_1 T) + (\alpha_2 T^2) + \ldots + (\alpha_n T^n))$ → polynomial

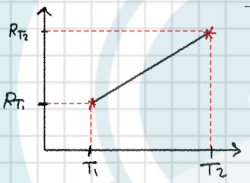
↳ * General formula

** → $R = R_0(1 + \alpha(T-T_0) + \alpha_2(T-T_0)^2 \text{ ---}$

→ in certain range the relationship could be Linear.

$R = R_0(1+\alpha_1 \Delta T) = R_0(1+\alpha_1(T-T_0))$.

* platinum used for range up to 200 c° → 200° بين اعلى حرارة و أقل حرارة



$\alpha = \frac{1}{R_0}\left(\frac{\Delta R}{\Delta T}\right)$, $R = R_0(1 + \alpha_1(T-T_0) + \alpha_2(T-T_0)^2 \text{ ---})$

case (1) [linear] case (2) [Quadratic]

* بطاي الحالة بيج اعمل معادلتين.

بيج اعرفلها قيمة بناءًا على النظام الي معطي

using values of resistance and temperature at three different points. Two equations are formed and values of α_1 and α_2 are calculated from these.

Example 5.17. Use the following values of resistance versus temperature for an RTD to find the linear and quadratic approximations of resistance between 100°C and 130°C about a mean temperature of 115°C.

Temperature, C°	90	95	100	105	110	115	120	125	130
Resistance Ω	562.66	568.03	573.40	578.77	584.13	589.48	594.84	600.18	605.52

(R) اذا ما اعطت قيمة $\frac{R_2+R_1}{2}$ منوخذ

Solution.

1. Linear Expansion : Given :

$\theta_1 = 100°C, \theta_2 = 130°C, \theta_0 = 115°C$

$R_{\theta_1} = 573.40\ \Omega, R_{\theta_2} = 605.52\ \Omega, R_{\theta_0} = 589.48\ \Omega$

* About nominal (mean) temp. 115°

$R_0 = 589.48$, (mid point).

$T_1 = 100\ C°$

$T_2 = 130\ C°$

$T_0 = 115\ C°$

* $\alpha = \frac{\text{slop}}{R_0} = \frac{1}{R_0}\left(\frac{\Delta R}{\Delta T}\right)$

1 linear :

$\alpha = \frac{1}{R_0}\left(\frac{R_2-R_1}{T_2-T_1}\right) = \frac{1}{589.48}\left(\frac{605.52-573.4}{130-100}\right)$

$\alpha = 0.00182 C°$ around mid point 115C°

→ $R = R_0(1+\alpha(T-T_0))\Omega$

$R = 589.48\ (1 + 0.00182\ (T-115))\Omega$.

* $\frac{1}{C}$ for α_1

* $\frac{1}{C^2}$ for α_2 $(T-115)^2 = C^2$ so $\alpha_2 = \frac{1}{C^2}$

2 Quadratic Expansion :

$R = R_0(1+\alpha_1(T-T_0) + \alpha_2(T-T_0))$.

→ for 100C° :

$573.40 = 589.48\ (1 + \alpha_1(100-115) + \alpha_2(100-115)^2)$

$\frac{573.40}{589.48} - 1 = -15\alpha_1 + 15^2\alpha_2 \text{ ---} ①$

→ for 180C° :

$605.52 = 589.48\ (1 + \alpha_1(130-115) + \alpha_2(130-115)^2)$.

$\frac{605.52}{589.48} - 1 = 15\alpha_1 + 15^2\alpha_2 \text{ ---} ②$

$-0.02727 = -15\alpha_1 + 225\alpha_2$

$0.02721 = 15\alpha_1 + 225\alpha_2$ −

$-0.0545 = -30\alpha_1$ → $\alpha_1 = 1816 * 10^{-3}$

using values of resistance and temperature at three different points. Two equations are formed and values of α_1 and α_2 are calculated from these.

Example 5.17. Use the following values of resistance versus temperature for an RTD to find the linear and quadratic approximations of resistance between 100°C and 130°C about a mean temperature of 115°C.

Temperature, C°	90	95	100	105	110	115	120	125	130
Resistance Ω	562.66	568.03	573.40	578.77	584.13	589.48	594.84	600.18	605.52

Solution.

1. Linear Expansion : Given :

$$\theta_1 = 100°C,\ \theta_2 = 130°C,\ \theta_0 = 115°C$$

$$R_{\theta_1} = 573.40\ \Omega,\ R_{\theta_2} = 605.52\ \Omega,\ R_{\theta_0} = 589.48\ \Omega$$

From Eqn. 5.57,

$$\alpha_{\theta_1} = \alpha_1 = \frac{1}{R_{\theta_0}} \times \frac{R_{\theta_2} - R_{\theta_1}}{\theta_2 - \theta_1}$$

$$= \frac{1}{589.48} \times \frac{605.52 - 573.40}{130 - 100} = 0.00182\ /°C$$

∴ The linear approximation is :

$$R_\theta = 589.48\ [1 + 0.00182\ (\theta - 115)]\ \Omega.$$

2. Quadratic Expansion : The resistance R_θ at any temperature θ°C is given by :

$$R_\theta = R_{\theta_0}\ [1 + \alpha_1\ \Delta\theta + \alpha_2\ (\Delta\theta)^2]$$

We can find the quadratic terms, by forming two equations using two points about the mean temperature $\theta_0 = 115°C$.

We have, $R_{\theta_0} = 589.48\ \Omega$ at $\theta_0 = 115°C$.

Now using 100°C and 130°C as the two points, we have :

$$573.40 = 589.48\ [1 + \alpha_1\ (100 - 115) + \alpha_2\ (100 - 115)^2]$$

$$605.52 = 589.48\ [1 + \alpha_1\ (130 - 115) + \alpha_2\ (130 - 115)^2]$$

From above have,

$$\alpha_1 = 1.823 \times 10^{-3}/°C \text{ and } \alpha_2 = -\ 0.22 \times 10^{-6}/(°C)^2$$

Hence,

$$R_\theta = 589.48\ [1 + 1.823 \times 10^{-3}\ (\theta - 115) - 0.22 \times 10^{-6}\ (\theta - 115)^2]\ \Omega.$$

Example 5.18. A platinum thermometer has a resistance of 100 Ω at 25°C. (*a*) Find its resistance at 65°C if the platinum has a resistance temperature co-efficient of 0.00392/°C. (*b*) If the thermometer has a resistance of 150 Ω, calculate the temperature.

Solution. (*a*) Using the linear approximation, the resistance at any temperature θ°C, is

$$R_\theta = R_{\theta_0}\ [1 + \alpha_{\theta_0} \Delta\theta]$$

∴ Resistance at 65°C is,

$$R_{65} = 100\ [1 + 0.00392\ (65 - 25)]$$

$$= 115.68\ \Omega.$$

(*b*) Suppose θ is the unknown temperature,

$$150 = 100\ [1 + 0.00392\ (\theta - 25)]$$

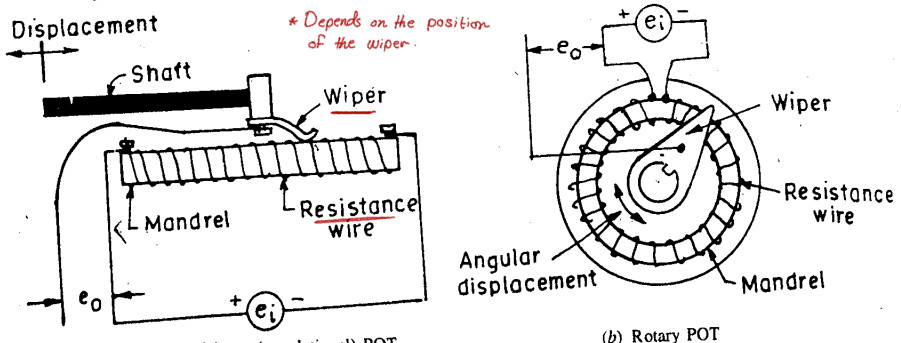
or $\theta = 152.55°C$.

Example 5.19. A copper resistor at 20°C is to used to indicate the temperature of bearings of a machine. What resistance should not be exceeded if the maximum bearing temperature is not to exceed 150°C ? The resistance temperature co-efficient of copper is 0.00393/°C at 20°C

This property may be used for measurement of **temperature.** Thus electrical resistance transducers have a wide field of application.

5.11. POTENTIOMETERS

Basically a resistance potentiometer, or simply a **POT**, (a resistive potentiometer used for the purposes of voltage division is called a **POT**) consists of a resistive element provided with a sliding contact. This sliding contact is called a **wiper**. The motion of the sliding contact may be translatory or rotational. A linear pot and a rotary pot are shown in Fig. 5.24 (*a*) and (*b*) respectively.



(*a*) Linear (translational) POT (*b*) Rotary POT

Fig. 5.24. Resistive potentiometers (POTs)

Some **POTs** use the combination of the two motions, *i.e.* translational as well as rotational. These POTs have their resistive element in the form of a helix and, therefore, they are called **helipots.**

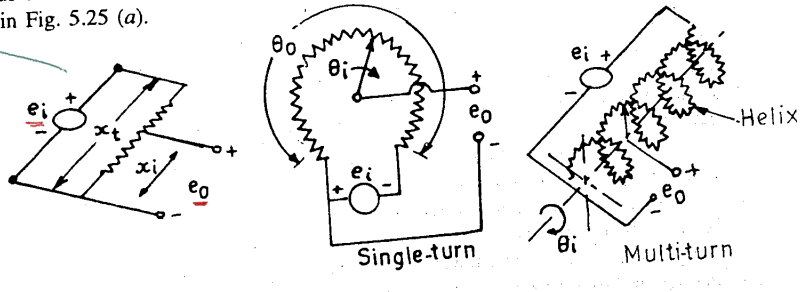
The translational resistive elements are straight devices and have a stroke of 2 mm to 0.5 m. The rotational devices are circular in shape and are used for measurement of angular displacement. They may have a full scale angular displacement as small as 10°. A full single turn potentiometer may provide accurate measurements upto 357°. Multiturn potentiometers may measure upto 3500° of rotation through use of **helipots.**

The helical resistive elements are multiturn rotational devices which can be used for measurement of either translational or rotary motion. The resistive element of the POT may be excited by either d.c. or a.c. voltage. The POT is a **passive transducer** since it requires an external power source for its operation.

The resistive body of potentiometer may be wire wound. A very thin, 0.01 mm diameter of platinum or nickel alloy is carefully wound on an insulated former. The resistance elements are also made up from cermet, hot moulded carbon, carbon film and thin metal.

Fig. 5.25 shows the diagrams for translational, single turn rotational, and multiturn helix potentiometers.

Let us confine our discussion of d.c. excited potentiometers. Consider a translational potentiometer as shown in Fig. 5.25 (*a*).



(*a*) Translational (*b*) Rotational (*c*) Helipot

Fig. 5.25. Diagrams for translational, rotational and helipots.

Let, e_i and e_o = input and output voltages respectively ; V,
x_t = total length of translational pot ; m,
x_i = displacement of wiper from its zero position ; m,
R_p = total resistance of the potentiometer ; Ω.

If the distribution of the resistance with respect to translational movement is linear, the resistance per unit length is R_p/x_t.

The output voltage under ideal conditions is :

$$e_0 = \left(\frac{\text{resistance at the output terminals}}{\text{resistance at the input terminals}} \right) \times \text{input voltage}$$

$$= \left[\frac{R_p(x_i/x_t)}{R_p} \right] e_i = \frac{x_i}{x_t} \times e_i \qquad ...(5.28)$$

Under the ideal circumstances, the output voltage varies linearly with displacement as shown in Fig. 5.26 (*a*).

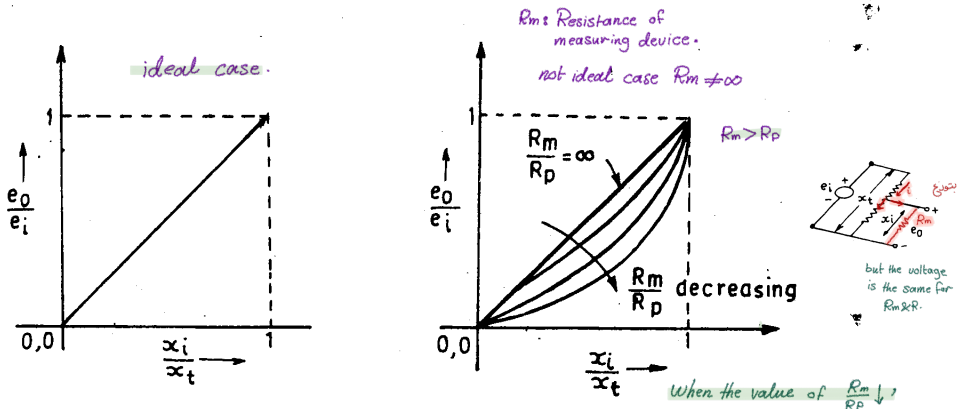


Fig. 5.26. Characteristics of potentiometers.

Sensitivity $$S = \frac{\text{output}}{\text{input}} = \frac{e_o}{x_i} = \frac{e_i}{x_t} \qquad ...(5.29)$$

Thus under ideal conditions the sensitivity is constant and the output is faithfully reproduced and has a linear relationship with input. The same is true of rotational motion.

Let θ_i = input angular displacement in degrees, and θ_t = total travel of the wiper in degrees.

$\therefore$ Output voltage $e_0 = e_i \cdot (\theta_i/\theta_t)$ ...(5.30)

This is true of single turn potentiometers only.

The circuits shown in Fig. 5.25 are called **potentiometer dividers** since they produce an output voltage which is a fraction of the input voltage. Thus the input voltage is "divided". The potential divider is a device for dividing the potential in a ratio determined by the position of the sliding contact.

Eqns. 5.29 and 5.30 are based upon the assumption that the distribution of resistance with respect to linear or angular displacement is uniform and the resistance of the voltage measuring device (*i.e.* output device) is infinite. However, in practice, the

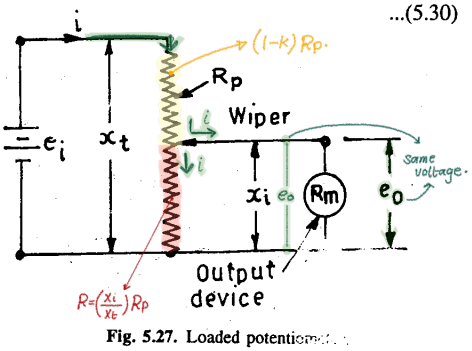


Fig. 5.27. Loaded potentiom...

① * the equivalent of R & Rm

$$= \frac{R_p\left(\frac{x_i}{x_t}\right)^K * R_m}{R_p\left(\frac{x_i}{x_t}\right)^K + R_m} = \frac{R_p K \cdot R_m}{R_p K + R_m}$$

② * The equivalent resistant (total).

$$(1-K)R_p + \frac{R_p(K) \cdot R_m}{R_p(K) + R_m} = \frac{(R_p^2K - R_p^2K^2 + R_m R_p - R_m R_p K) + R_p R_m K}{R_p(K) + R_m}$$

$$R = \frac{R_p^2 K(1-K) + R_m R_p}{R_p(K) + R_m}$$

③ $i = \frac{\text{Total input voltage}}{\text{Total Resistance}} = \frac{e_i}{R} = \frac{e_i(R_p(K) + R_m)}{R_p^2 K(1-K) + R_m R_p}$

④ The output voltage = $(i) * (R)$ ← parallel of R & Rm.

$$= \frac{e_i(R_p(K) + R_m)}{R_p^2 K(1-K) + R_m R_p} \cdot \left(\frac{R_p K \cdot R_m}{R_p K + R_m}\right)$$

$$= \frac{e_i(K)}{\frac{R_p}{R_m}(K(K-1)) + 1}$$

in the ideal case → $R_m = \infty$, no loading effect.

$\left(\frac{R_p}{R_m}(K(K-1))\right) =$ zero

$e_0 = e_i(K) = e_i\left(\frac{x_i}{x_t}\right)$

output terminals of the **pot** are connected to a device whose impedance is finite. Thus, when an electrical instrument, which forms a load for the **pot** and is connected across the output terminals, the indicated voltage is less than that given by Eqn. 5.29. The error, which is referred to as a **loading error** is caused by the input resistance of the output device.

Let us consider the case of a translational potentiometer as shown in Fig. 5.27. Let the resistance of a meter or a recorder monitoring the output be R_m.

As explained earlier if the resistance across the output terminals is infinite, we get a linear relationship between the output and the input voltage.

$$e_0 = (x_i/x_t)\ e_i = Ke_i \qquad ...(5.31)$$

where $K = x_i/x_t$

However, under actual conditions the resistance, R_m, is not infinite. This causes a non-linear relationship between the output and input voltages.

5.11.1. Loading Effect. The resistance of the parallel combination of load resistance and the portion of the resistance of the potentiometer is :

$$\frac{(x_i/x_t)\ R_pR_m}{(x_i/x_t)\ R_p + R_m} = \frac{K\ R_pR_m}{K\ R_p + R_m} \qquad ...(5.32)$$

The total resistance seen by the source is :

$$R = R_p\ (1 - K) + \frac{K\ R_pR_m}{K\ R_p + R_m} = \frac{KR_p^2\ (1 - K) + R_pR_m}{K\ R_p + R_m} \qquad ...(5.33)$$

$$\therefore \text{ Current } \qquad i = \frac{e_i}{R} = \frac{e_i\ (K\ R_p + R_m)}{K\ R_p^2\ (1 - K) + R_pR_m}$$

The output voltage under load conditions is :

$$e_o = i\ \frac{K\ R_pR_m}{K\ R_p + R_m} = \frac{e_i\ (K\ R_p + R_m)}{K\ R_p^2\ (1 - K) + R_pR_m} \cdot \frac{KR_pR_m}{(K\ R_p + R_m)}$$

$$= \frac{e_iK}{K\ (1 - K)\ (R_p/R_m) + 1} \qquad ...(5.34)$$

The ratio of output voltage to input voltage under load conditions is :

$$\frac{e_0}{e_i} = \frac{K}{K\ (1 - K)\ (R_p/R_m) + 1} \qquad ...(5.35)$$

The Eqn. 5.35 shows that there exists a non-linear relationship between output voltage e_0 and input displacement x_i since $K = x_i/x_t$. In case $R_m = \infty$, $e_o/e_i = K$.

It is evident from Eqn, 5.35 that as the ratio of R_m/R_p decreases, the non-linearity goes on increasing. This is shown in Fig. 5.26 (*b*). Thus, in order to keep linearity, the value of R_m/R_p should be as large as possible. However, when we have to measure the output voltage with a given meter, the resistance of the potentiometer, R_p, should be as small as possible.

$\therefore$ Error = output voltage under load – output voltage under no load

$$= \frac{e_i\ K}{[K\ (1 - K)\ (R_p/R_m) + 1]} - e_i\ K = -\ e_i \left[\frac{K^2\ (1 - K)}{K(1 - K) + R_m/R_p)} \right] \qquad ...(5.36)$$

Based upon full-scale output, this relationship may be written as :

$$\%\ \varepsilon = -\left[\frac{K^2\ (1 - K)}{K\ (1 - K) + (R_m/R_p)} \right] \times 100 \qquad ...(5.37)$$

Except for the two end points where $K = 0$ *i.e.* $x_i = 0$ and $K = 1$ where $x_i = x_t$ the error is always negative. Fig. 5.28 shows a plot of the variation in error with the slider position for different ratios of the load (output device or meter) resistance to the potentiometer resistance.

Resolution = minimum meas...
= 10 × 1/200 = 0.05 mm.

Example 5.5. A variable potential divider has a total resistance of 2 kΩ and is fed from a 10 V d.c. supply. The output is connected to a load resistance of 5 kΩ. Determine the loading errors for the wiper positions corresponding to $K = x_i/x_t$ = 0, 0.25, 0.5, 0.75, and 1.0. Use the results to plot a rough graph of error versus x_i/x_t.

Solution. We have $R_p = 2$ kΩ and $R_m = 5$ kΩ

From Eqn. 5.36, error is,

$$- e_i \left[\frac{K^2 (1 - K)}{K (1 - K) + R_m/R_p} \right]$$

Substituting the values, the results are tabulated below :

K	0	0.25	0.5	0.75	1
Error, V	0	– 0.174	– 0.454	– 0.524	0

The graph between error versus $K = x_i/x_t$ is plotted in Fig. 5.31. (The errors are no doubt – ve but they are shown as + ve in Fig. 5.31)

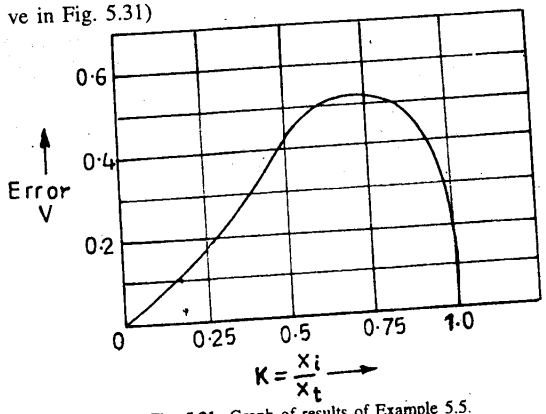


Fig. 5.31. Graph of results of Example 5.5.

Example 5.6. A resistive potential divider R_1 R_2 with a resistance of 5000 Ω and a shaft stroke of 125 mm is used in the arrangement shown in Fig. 5.32. Potentiometer R_3R_4 has a resistance of 5000 Ω and $e_i = 5.0$ V. The initial position to be used as reference point is such that $R_1 = R_2$ *i.e.* the wiper is at midstroke. At the start of the test potentiometer R_3R_4 is adjusted so that the bridge is balanced and $e_o = 0$. Assuming that the displacement being measured will move a maximum distance of 12.5 mm towards A, calculate the value of e_o.

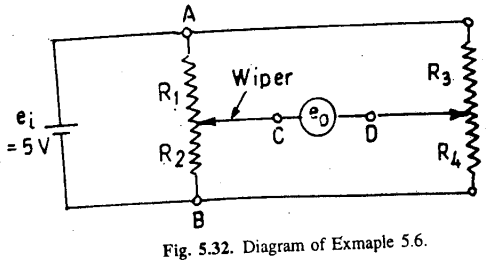


Fig. 5.32. Diagram of Exmaple 5.6.

Solution. Total length of AB = 125 mm Midpoint of AB = 62.5 mm from either A or B. If the wiper moves 12.5 inward towards A from midstroke, its distance from B becomes 62.5 + 12.5 = 75 mm.

File (1)

* indirect methods of measurement:
- Force using Diaphragm.
(based on displacement).

→ equations from this file will be given.

5 Primary Sensing Elements and Transducers

5.1. INTRODUCTION

The measurand in an instrumentation system makes its first contact with a *Primary Detection Element* or an *Input Device*. There is a multiplicity and variety of measurands to be measured. These include process variables like temperature, pressure and flow rate which are widely employed in process and production plants. The measurands also include electrical quantities like current, voltage, resistance, inductance, capacitance, frequency, phase angle, power and magnetic quantities like flux, flux density, reluctance etc.

All these quantities require a primary detection element and/or a transducer to be converted into another analogous format which is acceptable by the later stages of the measurement system. The measurand or the input signal is called an *information* for the measurement system. The information may be in the form of a physical phenomenon or it may be an electrical signal. The process of detection and conversion of the information into an acceptable form requires energy. This energy may be extracted from the measurand, but in that case it will not be represented in its faithful form as it would be subjected to loading errors. In order that a measurand is represented in its faithful form undistorted, no energy should be extracted from it during the process of conversion *i.e.* it should not be subjected to any kind of loading effects. In fact, efforts should be made to supply energy required for conversion from outside sources so that the measurand is not distorted during the process of conversion in order that it be faithfully reproduced in its analogous form. The ideal conversion is where absolutely no energy is extracted from the measurand during the process of conversion and all the energy that is required for conversion is supplied from outside, so that the measurand is not distorted and the analogous output of the detector is a faithful representation of the measurand.

5.2. MECHANICAL DEVICES AS PRIMARY DETECTORS

In order to extract information from mechanical systems, only mechanical displacement or velocity can be used as detectable variables, and therefore the importance of mechanical sensing elements is obvious. Some of the commonly used mechanical sensing elements are springs – which convert a force or a torque into a displacement ; a diaphragm, a capsule, bellows or Bourdon tube – which convert pressure into a displacement, a bimetallic strip converts temperature into a displacement ; a mass damper system is used for measurement of acceleration, velocity and displacement. Some input devices may involve more than one mechanical conversion, for example, fluid flow measurements may involve conversion of fluid rate into pressure differential using an orifice, venturi tube or pitot tube and then in turn this pressure is converted into displacement for purposes of measurement.

There are a number of mechanical quantities which are to be measured. Some of these quantities are listed in table 5.1 along with their modes of operation for the purposes of measurement.

Table 5.1
Mechanical Quantities and their Modes of Operation

Type	*Operation*
A. Contacting spindle, pin or finger	Displacement to displacement
B. Elastic Member	
1. Proving ring	Force to displacement.
2. Bourdon tube	Pressure to displacement.
3. Bellows	Pressure to displacement.
4. Diaphragm	Pressure to displacement.
5. Spring	Force to displacement.
C. Mass	
1. Seismic mass	Forcing function to displacement.
2. Pendulum scale	Force to displacement.
3. Manometer	Pressure to displacement.
D Thermal	
1. Thermocouple → voltage	Temperature to electric current.
2. Bimaterial → Resistance	Temperature to displacement.
3. Temp-stick	Temperature to phase.
E Hydropneumatic	
1. Static	
(*a*) Float	Fluid level to displacement.
(*b*) Hydrometer	Specific gravity to displacement.
2. Dynamic	
(*a*) Orifice	Velocity to pressure.
(*b*) Venturi	Velocity to pressure.
(*c*) Pitot tube	Velocity to pressure.
(*d*) Vanes	Velocity to force.
(*e*) Turbines	Linear to angular velocity.

using electrical signal to measure the temp.

⇒ indirect measuring

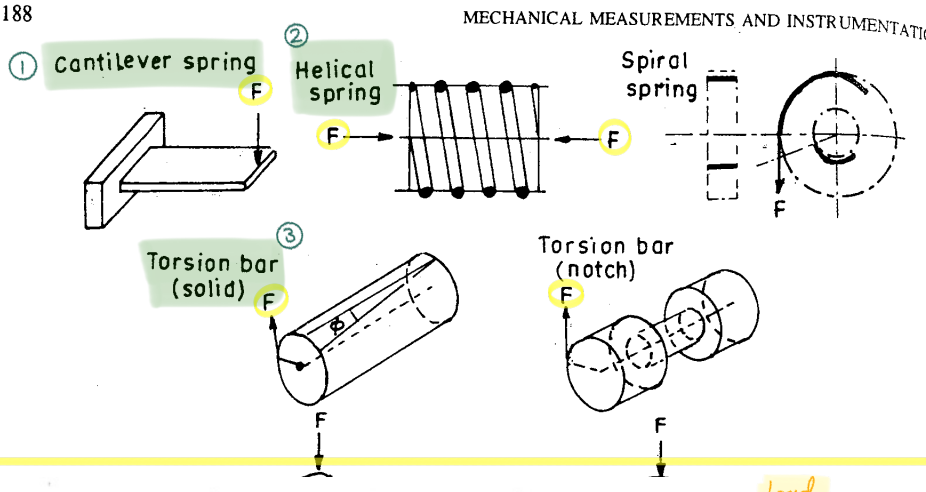
These mechanical quantities include force, pressure, displacement, flow rate, temperature and the list is perhaps unending.

The initial concept of converting an applied force into a displacement is basic to many types of primary sensing elements. The mechanical elements which are used to convert the applied force into displacement are usually elastic members. There are many types of these elastic members. They can be classified into three categories, although some elastic members may fall into a combination of these categories. The three categories are :

(*i*) Direct tension or compression type (*ii*) Bending type, (*iii*) Torsion type.

5.3. MECHANICAL SPRING DEVICES

Most mechanical-input measuring systems employ mechanical springs of one form or another. The displacements are usually small and engineering approximations for small displacements or deflections are valid. Various common types of springs are shown in Fig. 5.1. These range from cantilever, helical and spiral springs to torsion bars, proving (proof) rings and spring flexure pivots.



higher Force ⟹ higher desplacement at the endpoint.

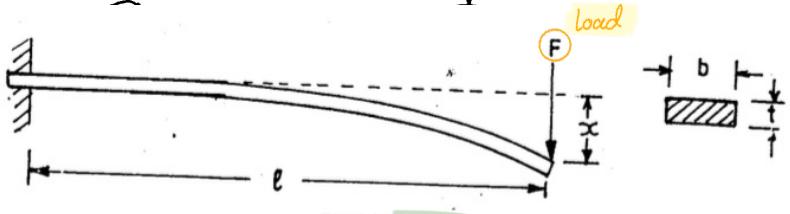


Fig. 5.2. Cantilever.

Deflection at the free end $x = Fl^3/3\,EI$ ...(5.1)

where (F) = applied force ; N, l = length of cantilever ; m, (unknown (will be measured).)

E = modulus of elasticity ; N/m²,

I = moment of inertia = $\left(\frac{1}{12}\right) bt^3$; m⁴,

b = width of cantilever ; m,

t = thickness of cantilever ; m.

Stiffness of cantilever $K = F/x = 3\,EI/l^3$ N/m ...(5.2)

5.3.2. Helical Spring. Fig. 5.3 shows a close coiled helical spring subjected to a compressive force F.

Displacement of spring :

$$x = \frac{8\,FD^3n}{Gd^4} \qquad ...(5.3)$$

where F = applied force ; N,

D = mean diameter of coiled spring ; m,

d = diameter of spring wire ; m,

n = number of wires,

G = shear modulus ; N/m².

Stiffness of spring $K = F/x$

$= Gd^4/8\,D^3n$ N/m. ...(5.4)

Maximum shear stress,

$\tau = 8\,FD/(\pi d^3)$ N/m². ...(5.5)

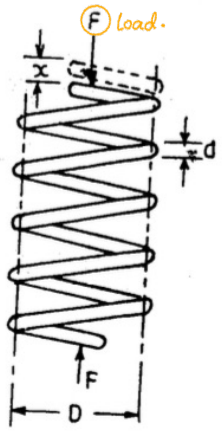


Fig. 5.3. Closed coiled helical spring.

5.3.3. Spiral Spring. Fig. 5.4 shows a flat spiral spring subjected to a torque T.

The deflection of the spring is :

the top and bottom of the proving ring. When the force is applied, the relative displacement can be measured. An LVDT is normally used for measurement of deflection which is of the order of 1 mm or so. Another method is to use strain gauges for measurement of strain caused by the applied force. The strain, then, can be used to compute the applied force.

5.3.6. Load Cells. Load cells utilize an elastic member as the primary transducer and strain gauges as secondary transducers as shown in Fig. 5.6.

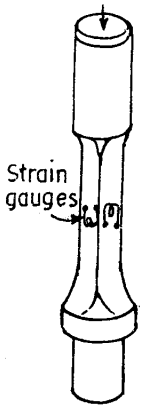


Fig. 5.6. Load cells.

5.3.7. Spring Flexure Pivots. Fig. 5.1 shows two different types of arrangements for flexure pivots, one for the single spring flexure pivot and the second for crossed spring flexure pivot. The crossed-spring flexure pivot is widely used in measurement work for the following reasons :

(*i*) it is practically frictionless

(*ii*) the pivot sensitivity *i.e.* the angular deflection per unit applied torque is virtually constant for angular relations less than 15°.

5.4. PRESSURE SENSITIVE PRIMARY DEVICES

Most pressure measuring devices use elastic members for sensing pressure at the primary stage. These elastic members are of many types and convert the pressure into mechanical displacement which is later converted into an electrical form using a secondary transducer. These devices are many a time known as **force summing devices.** Fig. 5.7 shows some of the commonly *pressure sensitive primary devices*

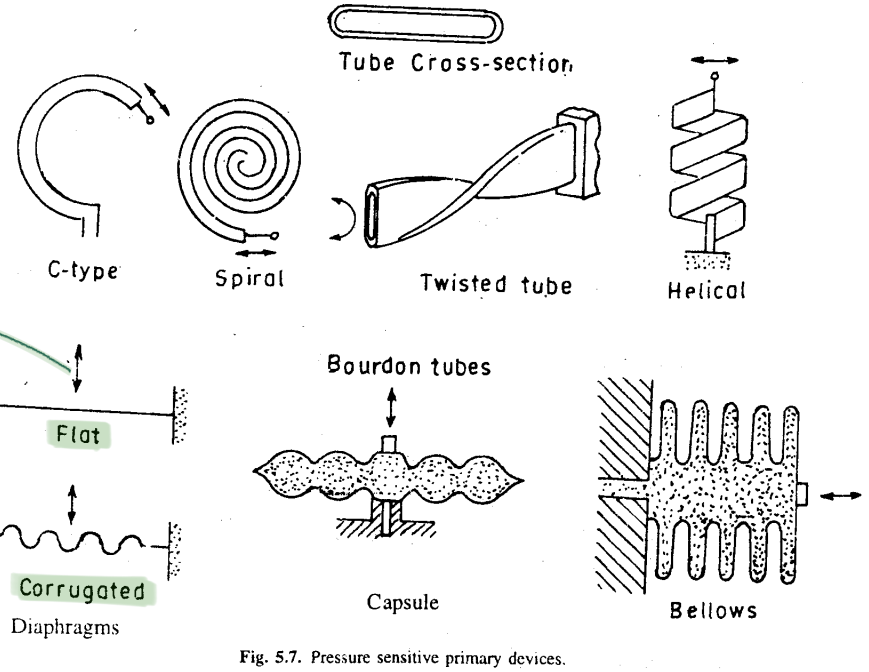


Fig. 5.7. Pressure sensitive primary devices.

The principle of working of these devices is explained as : the fluid whose pressure is to be measured is made to press the pressure sensitive element and since the element is an elastic member, it deflects causing

a mechanical displacement. The displacement is proportional to the pressure applied. The displacement is then measured with the help of electrical transducers. The output of the electrical transducers is proportional to the displacement and hence to the applied input pressure.

Some of the commonly used force summing devices are, (*i*) Bourdon tubes, (*ii*) Diaphragms and (*iii*) Bellows. They are described below :

5.4.1. Bourdon Tubes. These are designed in various forms like :

(*i*) C type (*ii*) spiral (*iii*) twisted tube and (*iv*) helical.

The Bourdon tubes are made out of an elliptically sectioned flattened tube bent in such a way as to produce the above mentioned shapes. One end of the tubes is sealed or closed and physically held. The other end is open for the fluid to enter. When the fluid whose pressure is to be measured enters the tube, the tube tends to straighten out on account of the pressure. This causes the movement of the free end and the displacement of this end is amplified through mechanical linkages. The amplified displacement of the free end may be used to move a pointer over a scale calibrated in units of pressure. Bourdon tubes normally measure gauge pressure. The materials used for Bourdon tubes are brass, phosphor bronze, beryllium copper, and steel.

5.4.2. Diaphragms. The movement of a diaphragm is a convenient way of sensing low pressures. A diaphragm is a circular disc of thin, springy metal firmly fixed at its rim. The unknown pressure is applied to one side of the diaphragm and since the rim of the diaphragm is rigidly fixed there is a deflection of the diaphragm. The displacement of the centre of the diaphragm is directly proportional to the pressure and therefore can be used as a measure of pressure.

The displacement of the diaphragm may be transmitted by an arm fastened to its centre to a mechanical linkage, which magnifies the displacement before applying it to a pointer of the indicating device.

The diaphragms are of two types :

(*i*) Flat, and (*ii*) Corrugated.

Corrugated diaphragms have an advantage over flat diaphragms because of the increased effective area and consequent greater sensitivity.

The diaphragms may be thin membranes. However, it is usual to employ thin circular plates which may either be clamped around the circumference between solid rings or are machined to form a solid piece of metal.

In many applications two or more diaphragms are joined to form a *capsule*, as shown in Fig. 5.7. Increasing the pressure in the capsule causes it to expand while decreasing the pressure causes it to contract. As all the diaphragms in the capsule act in unison, the displacement of the arm connected to centre of the capsule, is greater than that of a single diaphragm for the same pressure and hence the sensitivity is greater.

A flat diaphragm is shown in Fig. 5.8.

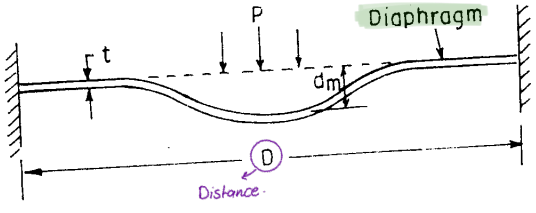


Fig. 5.8. Flat diaphragm.

The pressure is given by :

device to measure the pressure.

$$P = \frac{256\, E t^3 d_m}{3(1 - \nu^2) D^4} \text{ N/m}^2 \quad \ldots(5.12)$$

t: thickness of wire

d_m: max. displacement

E: modules of elasticity.

ν: poisson ratio.