CHAPTER 15

METROLOGY AND INSPECTION

Metrology is the science of measurement and industrial inspection. Instrument and gauges are the measuring tools that provide comparative and quantitative measurements of a product or component's dimensional, form and orientation attributes. Metrologists are intimately concerned with the design, manufacturing and testing of measuring tools.

15.1 LIMITS, TOLERANCES, AND FITS

Large number of parts of exactly same dimension cannot be produced commercially; actual dimension are always little larger or smaller than the desired ones. The desired dimension of a component is called the *nominal dimension*. The amount of deviation of the actual dimension from the nominal dimension is called the *tolerance*. The extreme permissible dimensions of a part are called *limits*.

Manufacturing tolerance is essential to facilitate *interchangeability* of parts that enable proper functioning of the assembled parts. Interchangeability refers to assembling a member of unit components taken at random from stock so as to build up a complete assembly without fitting or adjustment.

In graphical representations, *basic size* is the exact theoretical size from which limits of size are derived by the application of allowances and tolerances. It is represented by *zero line*. *Allowance* is the minimum clearance space between mating parts intentionally provided to secure the desired fit. *Interference* is the amount by which dimensions of the mating parts overlap. This is also called *negative allowance*.

15.1.1 Limit Systems

A limit system consists of a series of tolerances arranged to suit the specific range of sizes in order to enable specific classes of fit between mating components. The following are the two bases of limit systems [Fig. 15.1]:

1. Basic Hole System *Basic hole system* is a system of fits in which design size of the hole is the basic size from which allowance is subtracted to obtain the diameter of the shaft. The system is preferred because standard tooling (e.g. drills, reamers, broaches, plug gauges) whose size is not adjustable, and shaft can then easily be machined to fit.

2. Basic Shaft System *Basic shaft system* is a system of fits in which the design size of the shaft is the basic size to which allowance is added to obtain the diameter of the hole.

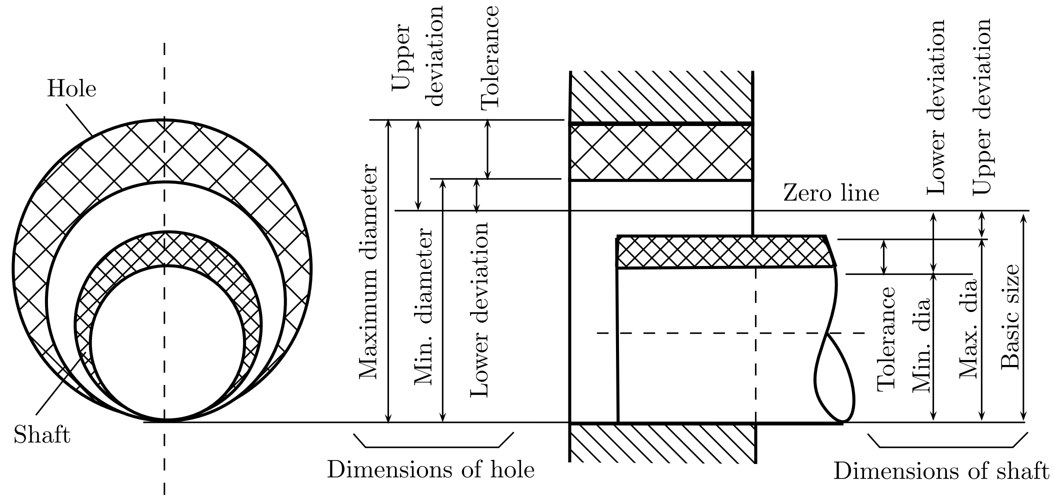

Figure 15.1 | Basic size and tolerances.

Deviation is the algebraic difference between the actual size and basic size. *Upper deviation* is the difference between the maximum limit size and the basic size. It is indicated as 'ES' for holes, and 'es' for shafts. *Lower deviation* is the algebraic difference between the minimum limit of a size and the basic size. It is indicated by 'EI' for holes and 'ei' for shafts.

The upper and lower deviations can be related to tolerance (IT) as by following formulas:

1. For shafts:

$$\text{es} = \text{ei} + \text{IT}$$

2. For holes:

$$\text{ES} = \text{EI} + \text{IT}$$

Fundamental deviation (δ) is either the upper or the lower deviation which is nearest to the zero line. This can be either for the shaft or for the hole.

15.1.2 Tolerance Systems

The tolerances on the dimensions can be specified in three ways:

1. Unilateral Tolerance System In *unilateral tolerance system*, the tolerance is provided on only one direction from the basic size, e.g. 3765^{+5}_{+2}, 3767^{+13}_{+0}.

   Unilateral tolerance system permits the variation in tolerance on a hole or shaft without seriously affecting the fit, therefore, it is the most commonly used in interchangeable manufacturing, especially where precision fits are required.

2. Bilateral Tolerance System In *bilateral tolerance system*, the tolerance is split into two parts and shown on both sides of the nominal size. For example, 3774^{+6}_{-7}, 3770^{+10}_{-11}.

   Bilateral system clearly indicates the theoretically desired size and deviations permitted on either side of the basic size. Thus, when tolerance is varied on a part, the basic dimensions of one or both the mating parts need changes to retain the same fit.

3. Limit Dimensioning System In *limit dimensioning*, the size and deviation of part are specified by only maximum and minimum dimensions. For example, $3735 - 3760$.

15.1.3 Fits

The degree of tightness or looseness between mating members is known as the *fit* of the members. It depends on the actual value of the individual tolerances of the mating components. The fits can be broadly classified into three categories [Fig. 15.2].

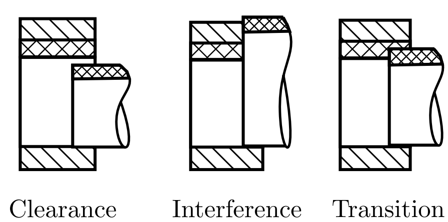

Figure 15.2 | Types of fits.

These are explained as follows:

1. *Clearance Fit* *Clearance fit* is one having limits of size so prescribed that a clearance always results when mating parts are assembled. A clearance fit has positive allowance; there is minimum positive clearance between high limit of the shaft and low limit of the hole. A clearance fit can be loose (no precision) or running fit (maintaining film lubrication).

2. *Interference Fit* *Interference fit* is one having limits of size so prescribed that an interference always results when mating parts are assembled. It is achieved by keeping the lower limit of the shaft greater than the upper limit of the hole.

3. *Transition Fit* *Transition fit* is one having limits of size so prescribed that the assembly of mating parts can result in either a clearance fit or an interference fit. This is achieved by keeping the upper limit on the shaft larger than the lower limit on the hole, and lower limit on the shaft smaller than the upper limit on the hole.

15.1.4 IS:919-1963

The system of limits and fits recommended in IS:919-1963 suggests 18 grades (IT01, IT0, IT1 to IT16) of fundamental tolerances and 25 types of fundamental deviations denoted by alphabets both for holes (A to ZC) and shafts (a to zc) in diametral steps up to 500 mm [Fig. 15.3].

Each grade has an associated value or formula for calculation of standard tolerance in terms of mean diameter D given by

$$D = \sqrt{D_1 D_2} \quad \text{mm}$$

and a parameter i, defined as

$$i = 0.45\sqrt[3]{D} + 0.001D \ \mu\text{m}$$

where D is in mm. The tolerances are determined based on the tolerance grade. Such as for IT7, the value of tolerance is $16i$. Other important values of tolerances according to tolerance grades are shown in Table 15.1

The shaft h for which the upper deviation is zero is called the *basic shaft* and the hole H for which the lower deviation is zero is called the *basic hole* [Fig. 15.3]. The values of the fundamental deviation (δ) for the hole from A to H are positive, whereas that for the shaft from a to h are negative. The values of the fundamental deviation for the hole from J to K are either positive or negative, whereas that for shaft form j to k are either positive or negative.

A hole or shaft is completely described if the basis size, followed by the appropriate letter and by the number of the tolerance grade is given. For example, a 25 mm H-hole with tolerance IT8 is indicated as 25 $H8$, a 25 mm f-shaft with tolerance grade IT7 is indicated as 25 $f7$.

Table 15.1 Tolerance grades

Grade	Value
IT5	$7i$
IT6	$10i$
IT7	$16i$
IT8	$26i$
IT9	$40i$
IT10	$64i$
IT11	$100i$
IT12	$160i$
IT13	$250i$
IT14	$400i$
IT15	$640i$
IT16	$1000i$

A fit is indicated by combining the designations for both the hold and shaft with the hole designation written first, regardless of the system. For example, 25 $H8f7$. Figure 15.3 shows that a fit comprising hole having tolerance between A and H and a shaft between a and h will certainly give a clearance fit.

To demonstrate the procedure, consider a shaft specified by 28h8. Basic size 28 mm comes in the range 18–30 mm. Therefore, mean diameter is

$$\begin{aligned} D &= \sqrt{D_1 \times D_2} \\ &= 23.2379 \text{ mm} \end{aligned}$$

Tolerance,

$$\begin{aligned} i &= 0.45\sqrt[3]{D} + 0.001D \ \mu\text{m} \\ &= 1.3074 \ \mu\text{m} \\ &= 0.0013074 \text{ mm} \end{aligned}$$

For basic shaft h upper deviation is zero. For IT8, the tolerance is $26i = 0.0339$ mm. Therefore, dimension of the shaft will vary between 28.000 mm and 28.000 − 0.0339 mm = 27.966 mm.

15.2 LINEAR MEASUREMENT

Linear metrology is the science of linear measurement for determination of the distance between two points in a straight line. The principle of linear measurement is to compare the dimensions to be measured and aligned with standard dimensions marked on the measuring instrument. Some important instruments for linear measurements are described as follows:

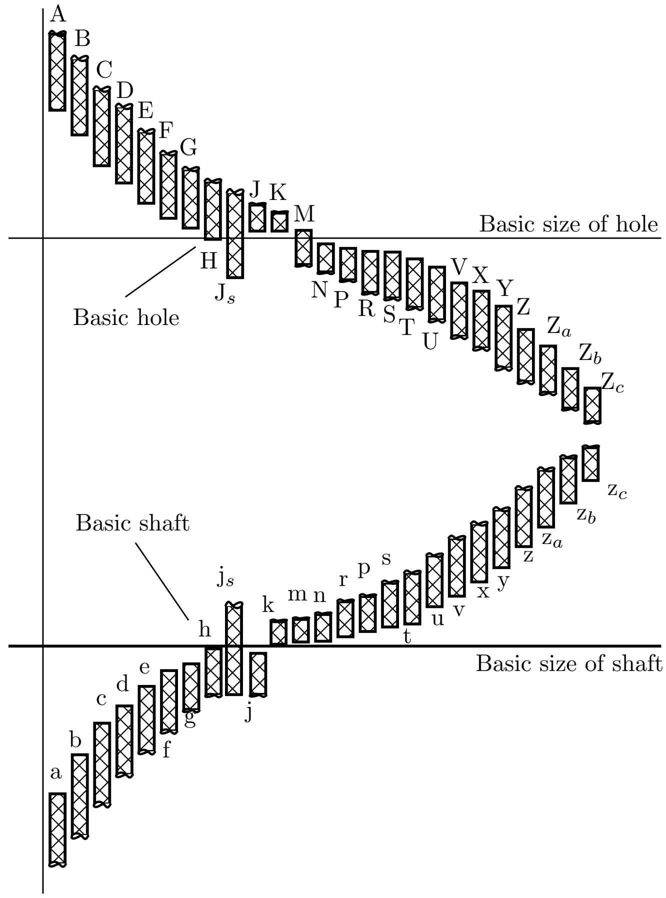

Figure 15.3 Fundamental tolerances in IS:919-1963.

1. *Steel Rule* *Steel rule* or *scale* is the simplest and the most commonly used linear measuring instrument. It measures an unknown length by comparing with the one previously calibrated.

2. *Calipers* A *caliper* is an end-standard measuring instrument to measure the distance between two points. Calipers typically use a precise slide movement for inside, outside, depth or step measurements. A caliper consists of two legs hinged at the top, with the ends of the legs spanning the part to be measured. The legs are made of alloy steel and are identical in shape, with the contact points equidistant from the fulcrum.

3. *Vernier Caliper* *Vernier caliper* is a combination of inside and outside calipers and has two sets of jaws in which one jaw (with a depth gauge) slides along a rule. The device is based on the observation of Pierre Vernier (1631) that human eye cannot discern the exact distance between two lines, but can tell when two lines coincide so as to form one straight line. Least count of a vernier caliper is determined by dividing the smallest division on the main scale by the total number of divisions on the vernier scale.

4. *Micrometers* *Micrometers* have greater accuracy than vernier calipers and are used in most of the engineering precision work involving interchangeability of component parts. The function of a micrometer is based on the principle of screw and nut. When a screw is turned through one revolution, the nut advances by one pitch distance. If circumference of the screw is divided into n equal parts, then rotation of one division will cause the nut to advance through pitch/n length (least count). Micrometers having accuracy of 0.01 mm are generally available which can increase upto 0.001 mm.

5. *Slip Gauges* *Slip gauges* are used in the manufacturing shops as length standards. They are not used for regular and continuous measurement. These are rectangular blocks having cross-section usually 32 mm × 9 mm but of thickness in standard series. Measuring surface of the gauge

blocks is finished to a very high degree of flatness and accuracy.

The gauges are wrung together by bringing them into contact with each other at right angles and then pressing them with a twisting motion and simultaneously turning them parallel. If gauges are in a good condition, wringing will take place easily.

6. Angle Plates Angle plates are used with surface plates for measurements. The two surfaces of face plates are perpendicular to each other. Angle plates are made from cast iron (minimum hardness 180 HB) in various sizes. These are provided with T-slots and long holes to facilitate their clamping and holding.

7. V-Blocks V-blocks are used for checking the roundness of cylindrical workpieces. The V-angle of the block is 90°. Primary use of V-blocks is to hold or move cylindrical workpieces along a precisely fixed axis.

8. Surface Gauges Surface gauge is a versatile instrument used with surface plates for layout work. The gauge consists of a heavy rigid base and spindle that carries a scriber. The rigid base has a perfectly flat bottom surface.

9. Feeler Gauges *Feeler gauges* are mostly used in engineering to measure the clearance between two parallel flat faces, such as piston and cylinder. These are called feeler gauges because these are neither forced to enter to gap nor to slide freely, but the use should feel the correctness personally. Feeler gauges consist of a set of gauging blades of different grades and thickness, which are assembled in a protective sheath.

10. Comparators *Comparators* are used for quick checking of large number of identical dimensions. These instruments cannot be used as an absolute measuring device, but only for comparing two dimensions.

11. Dial Indicators A dial indicator consists of a spring loaded plunger whose tip is used for measuring or gauging a surface. Movement of the plunger is magnified through the intermediate gearing to show with the pointer.

15.3 ANGULAR MEASUREMENT

Common angular measuring instruments read degrees directly from a circular scale scribed on the dial or circumference, such as *protractors* and *angle gauges*. Most common angle is right or perpendicular angle, therefore, squares are the most common devices for drawing them. Some other common instruments for angular measurements are described as follows:

1. Angle Gauges Angles gauges[1] are a series of fixed angles used for comparative assessment of the angles between two surfaces. Angles can be build up by proper combination of gauges.

2. Sine Bar *Sine bar* is a high precision angle measuring instrument. It is used in conjunction with a set of slip gauges. It is kept on two hardened rollers of accurately equal diameters spaced at a known dimension at each end. Thus, top and bottom surfaces of the bar are absolutely parallel to the center line of the rollers.

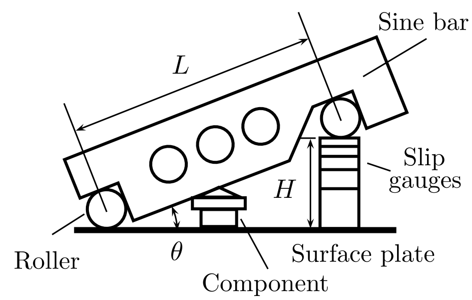

Figure 15.4 Sine bar.

As demonstrated in Fig. 15.4, the angle of the component surface is measured as

$$\theta = \sin^{-1}\frac{H}{L}$$

The bar is made of high-carbon, high chromium corrosion resistant steel and it is essentially hardened, ground, lapped and stabilized. *Relief holes* are drilled in its body to make it lighter and facilitate handling.

3. Clinometers *Clinometers* are the optical devices for measuring elevation angles above horizontal using spirit level mounted on a rotary member, which is carried in a housing. One face of the housing forms the base of the instrument. Angle of inclination of the rotary member carrying the level relative to its base is measured by a circular scale on the housing. [Fig. 15.5].

Clinometers are mainly used to determine the included angle of two adjacent faces of workpiece, large cutting tools, and milling cutter inserts.

4. Autocollimator Small angular tilts of a reflecting surface can be easily measured by an optical

[1]Tomlinson developed angle gauges in 1941.

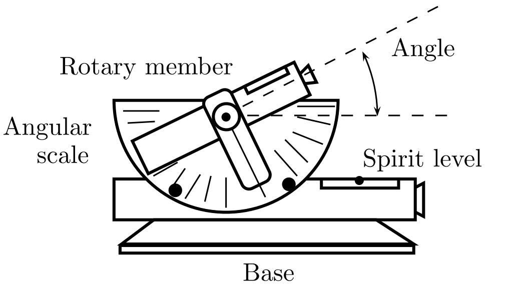

Figure 15.5 Clinometer.

instrument called *autocollimator*. The instrument consists of an infinite telescope and a *collimator* combined into one unit. This provides very sensitive and accurate readings.

When a parallel (collimated[2]) beam of light is projected through the lens, the beam is reflected back from the plane mirror along its own path to focus exactly at the position of the light source [Fig. 15.6].

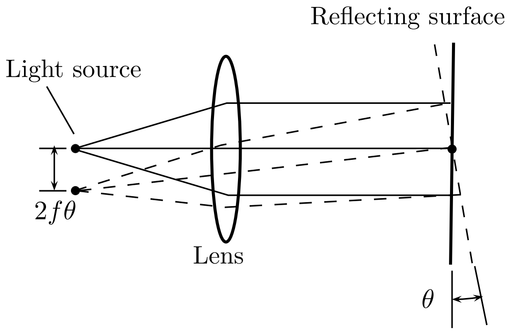

Figure 15.6 Principle of autocollimator.

If the reflector mirror is tilted through a small angle θ, the parallel beam deflects through twice the angle 2θ, thus shifting the focus of the image at a distance $2f\theta$ where f is the focal length of the lens.

5. *Taper Measurements* External tapers can be measured by using two rollers of the same diameter d [Fig. 15.7].

[2]Collimated light has parallel rays, therefore spreads minimally as it propagates. The word is related to "collinear" and implies light that does not disperse with distance (ideally), or that will disperse minimally (in reality).

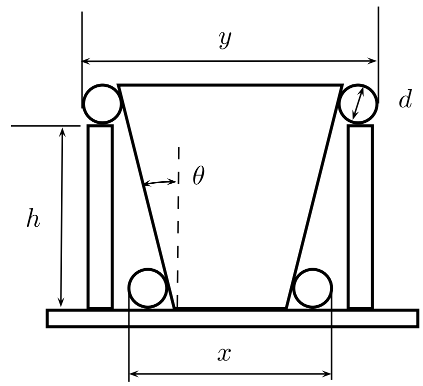

Figure 15.7 Measurements of external tapers.

The taper angle can be determined as

$$y = x + 2\frac{d}{2} + h\cot\theta$$

$$\theta = \cot^{-1}\left(\frac{y-x-d}{h}\right)$$

Internal tapers can be measured with the help of two balls of different sizes [Fig. 15.8].

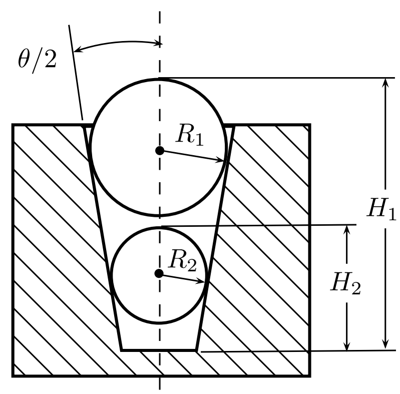

Figure 15.8 Measurements of internal tapers.

The taper angle can be determined as

$$\sin\left(\frac{\theta}{2}\right) = \frac{R_1 - R_2}{(H_1 - R_1) - (H_2 - R_2)} = \frac{R_1 - R_2}{(H_1 - H_2) - (R_1 - R_2)}$$

15.4 GAUGE DESIGN

Gauges or *limit gauges* are high precision instruments used for inspecting a given dimension whether it is within the specified tolerance limits or not rather than measuring. For this, a gauge consists of two elements [Fig. 15.9]:

1. A "GO" section which presents the maximum limit on the possible dimension of the shaft.
2. A "NO GO" section that presents the minimum limit on the dimension of the shaft.

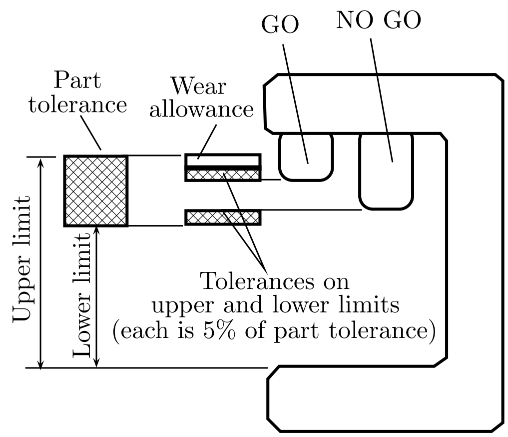

Figure 15.9 | Tolerances on gauges.

Tolerance is also essential in manufacturing of the GO and NO GO sections of the gauges. To prohibit a part with higher tolerance, tolerance in gauges is generally applied inside the part tolerance [Fig. 15.9]. Value of gauge tolerance is kept approximately 10% of the workpiece tolerance, which is equally distributed between the GO and NO GO sections. About 5% of the work tolerance is normally allowed as wear allowance to take care of abrasion of GO element, which experiences the relative movement with the part.

15.5 INTERFEROMETRY

Huygens' theory proposes that light is considered as wave motion propagated either as an electromagnetic wave of sinusoidal form. Wave characteristics of light are not apparent under ordinary conditions but when the two waves interact with each other, the wave effect is visible and it can be made useful for measuring applications. This is possible by interferometry techniques which enable the determination of size of end standards (slip gauges and end bars) directly in terms of wavelength of light source. White light is the combination of all the colors of the visible spectrum. This combination of all wavelengths of a visible spectrum and its form is not suitable for interferometry. Monochromatic light such as mercury, mercury 198, cadmium, krypton, krypton 86, thallium, sodium, and laser beams are used.

15.6 SURFACE MEASUREMENT

Surface finish plays an important role in the performance of machine elements. Friction and wear increases with surface roughness, thus adversely affecting the performance of bearings. Rough surfaces have reduced contact area in interference fit which reduces the holding capacity of the joints. Endurance strength of the component is greatly reduced due to poor surface finish.

There are variety of methods available for measurement of the roughness and determination of the statistical properties of surfaces. *Surface finish*[3] measurements can be grouped into two sets:

1. *Comparison-Based Methods* In this category, the surface texture is assessed by observation of the surface with the surface produced by same techniques. These methods include touch inspection, visual inspection, scratch inspection, microscope inspection, etc. These methods involve subjective judgment.

2. *Direct Measurement Methods* It is possible to get the numerical value of surface finish by using stylus probe type of instruments.

   One of the widely used techniques is the *mechanical profilometer*. This instrument directly traces the surface using a narrow diamond *stylus*, which produces a time-varying voltage output proportional to the height of the surface profile. Tomlison surface meter and Tayler–Habson's "Talysurf" are the two profilometers.

   An *optical profilometer* is a non-contact method for providing much of the same information as a stylus based mechanical profilometer. Non-contact profilometer does not touch the surface and the scan speeds are dictated by the light reflected from the surface and the speed of the acquisition electronics. Optical profilometers are more reliable because these are not damaged by surface wear. There are many different techniques which are currently being employed, such as laser triangulation (triangulation sensor), confocal microscopy (used for profiling of very small objects), low coherence interferometry and digital holography.

   Fiber-based optical profilometers scan surfaces with optical probes which send light interference signals back to the profilometer detector via an optical fiber.

[3]Refer the Chapter 14: Machining, where the fundamental concepts and definitions related to surface finish has been discussed in detail.