

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.

مادّة فائيل

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

to do the inspection,
 the diameter should be between
 the LML & MML, \rightsquigarrow accept.
 but if diameter $>$ LML \rightsquigarrow reject.
 $<$ MML. \rightsquigarrow "
 *not efficient for high mass
 production.
 \rightsquigarrow use two shaft with zero tolerance.
 (GO) to test the MML of the hole *
 (NOT GO) " " " LML " " " *

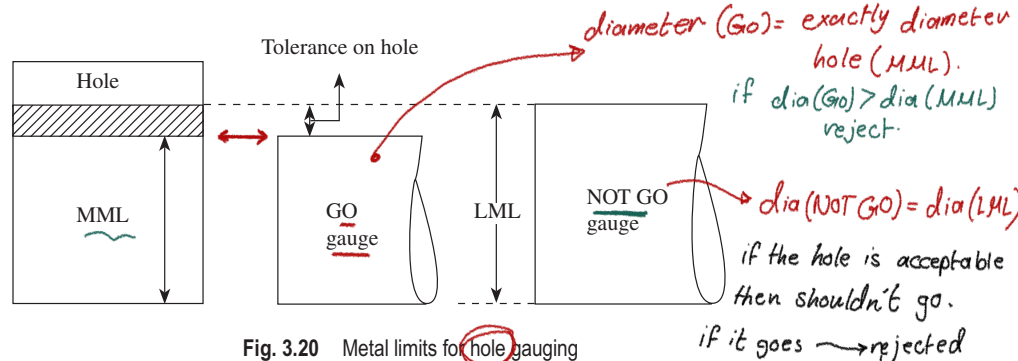


Fig. 3.20 Metal limits for hole gauging

To test the shaft \rightsquigarrow 2 holes.
 (GO) to test \rightsquigarrow MML
 (NOT GO) to test \rightsquigarrow LML

هنا جزء التالسية

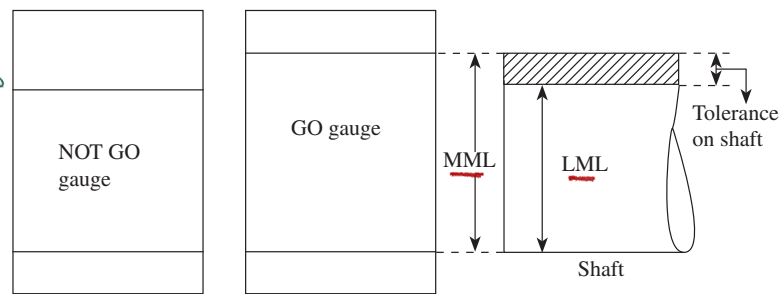


Fig. 3.21 Metal limits for shaft gauging

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

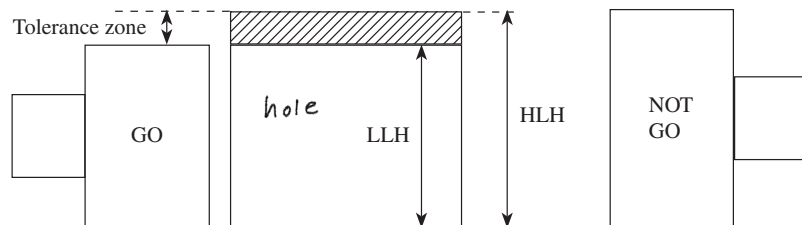


Fig. 3.22 GO and NOT GO limits of plug gauge

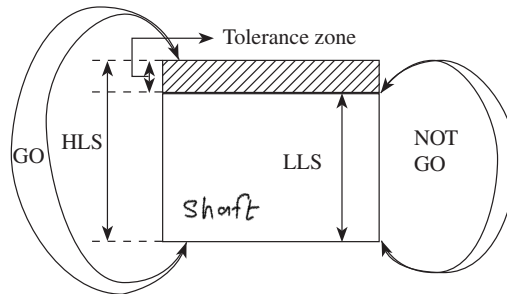


Fig. 3.23 GO and NOT GO limits of snap gauge

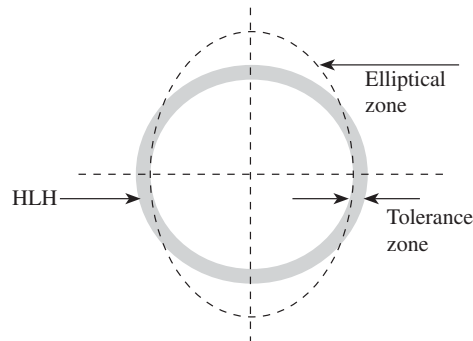


Fig. 3.24 Ovality in hole

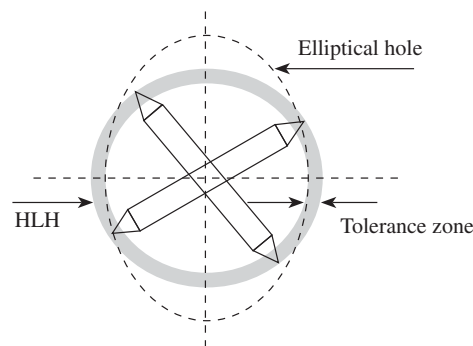


Fig. 3.25 Pin-type NOT GO to check ovality

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.

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

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.

- used in high mass production inspections.

3.6.6 Material for Gauges

harder than the tested material.

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

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.

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.

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.

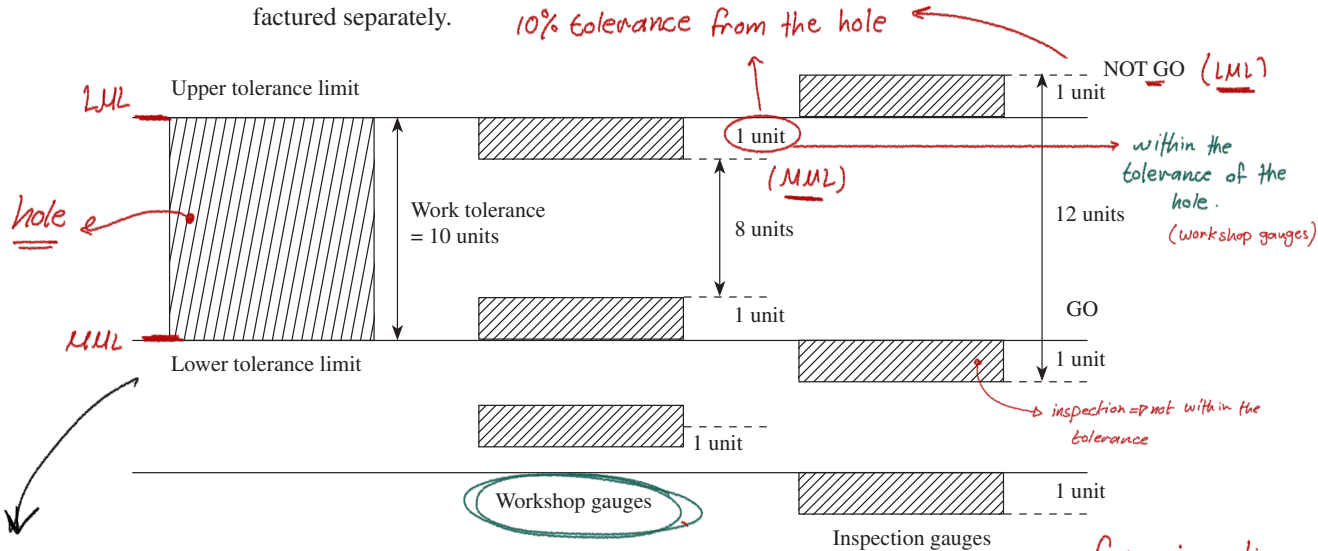


Fig. 3.26 Disposition of tolerances on workshop and inspection gauges

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.

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

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

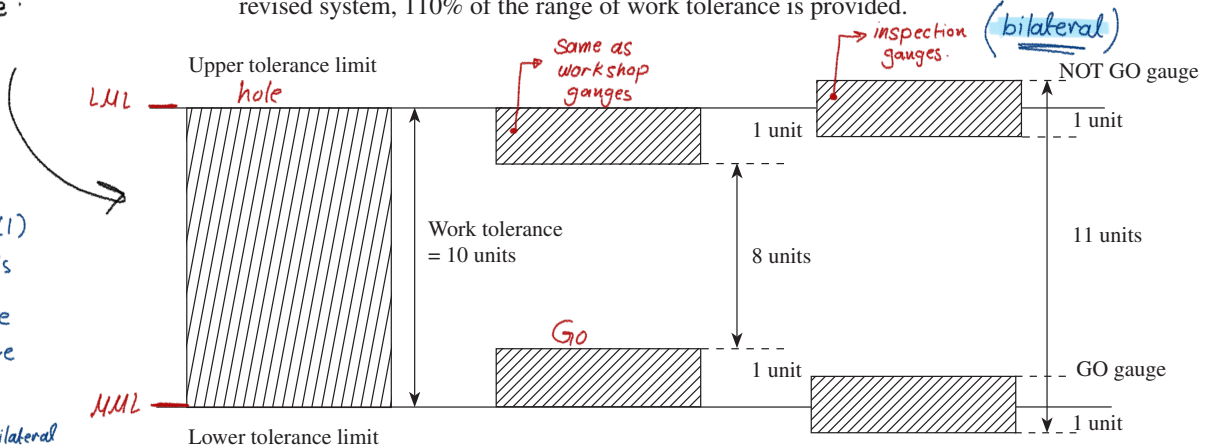


Fig. 3.27 Disposition of modified tolerances on workshop and inspection gauges

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

British System

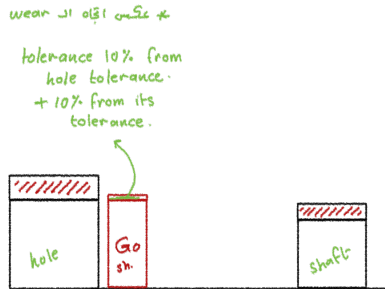
The present British system is in accordance with Taylor's principle and is widely accepted in industries. This system works according to the following guidelines:

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.



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 = $-16D^{0.44}$
- (f) wear allowance assumed to be 10% of gauge tolerance

* 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 اتجاه ال

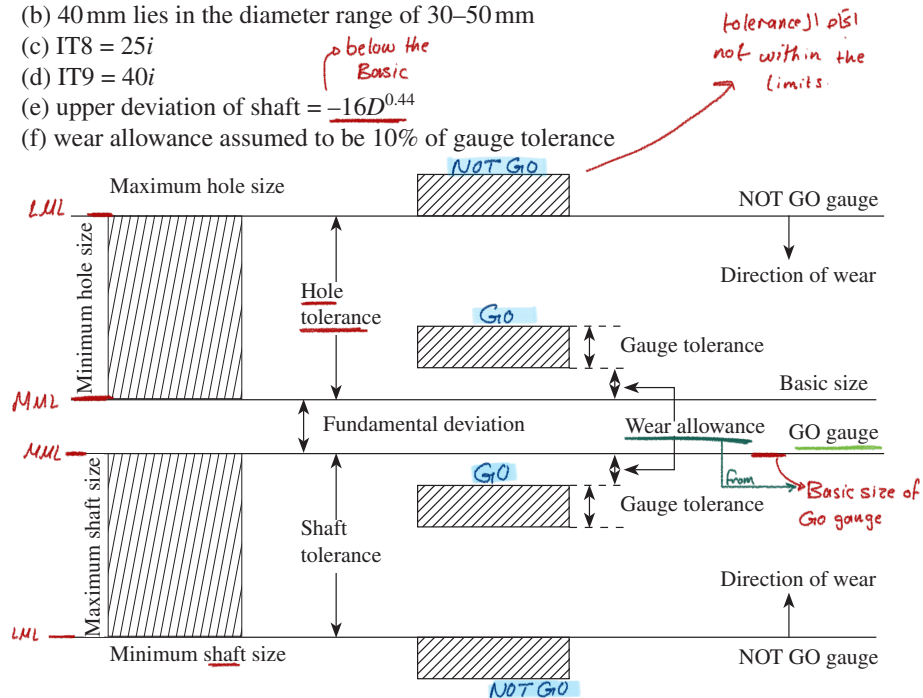
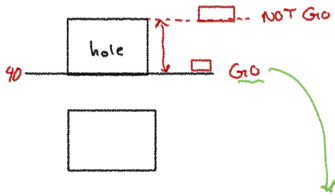


Fig. 3.28 Disposition of tolerances and allowances on gauges

Ex :

1. Design G₀/N₀T G₀ & H8 d₉

Hole (H) → D₁, D₂ ...
 $D = \sqrt{\frac{D_{max} + D_{min}}{2}}$
 IT₈
 T₉.



for the G₀ snap gauge
 LLG

tolerance for G₀/N₀T - G₀
 = 0.1 * (hole tolerance)
 = 0.1(0.039)
 = 0.0039 for both.

for the shaft
 (wear tolerance for
 G₀ snap gauge)
 = 0.1(G₀ tolerance)
 = 0.0039 mm

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

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

$$i = 0.453 (\sqrt[3]{38.7298}) + 0.001(38.7298) = 1.571 \mu\text{m}$$

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

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

For hole, the fundamental deviation is zero.

Hence, hole limits are as follows:

$$\text{LLH} = 40 \text{ mm}$$

$$\text{HLH} = 40.00 + 0.039 = 40.039 \text{ mm}$$

$$\text{Hole tolerance} = 40.039 - 40 = 0.039 \text{ mm}$$

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

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

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

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

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

Hence, shaft limits are as follows:

$$\text{HLS} = 40 - 0.080 = 39.92 \text{ mm}$$

$$\text{LLS} = 40 - (0.080 + 0.063) = 39.857 \text{ mm}$$

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.

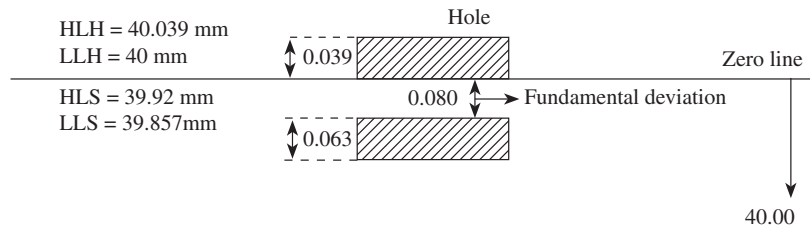


Fig. 3.29 Disposition of tolerances

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

+0.00429

Limits of GO plug gauge = 40^{+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

-0.0429

Limits of NOT GO plug gauge = 40^{+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

-0.08063

Limits of GO snap gauge = 40^{-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

-0.1430

Limits of NOT GO snap gauge = 40^{-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.

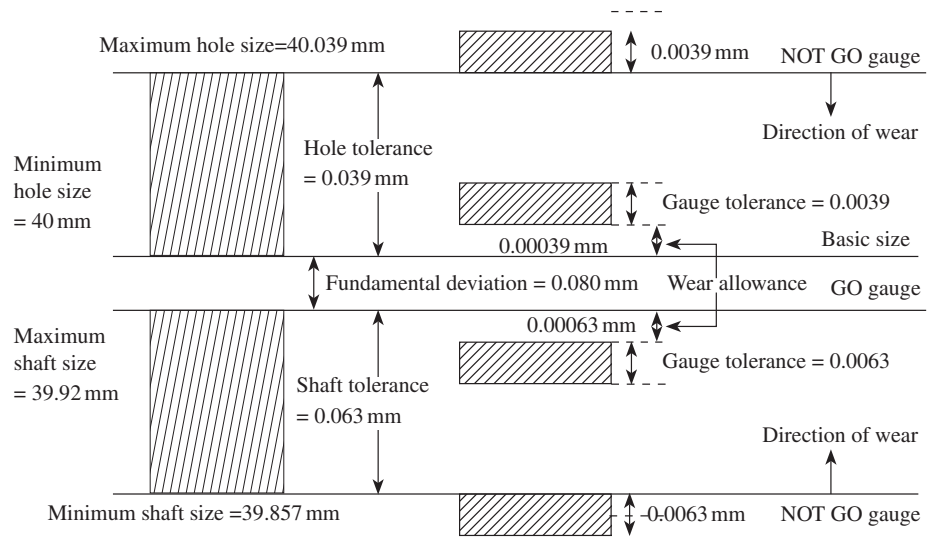


Fig. 3.30 Disposition of gauge tolerances and wear allowance

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 40mm with a tolerance of H7 and is as per Indian standard.

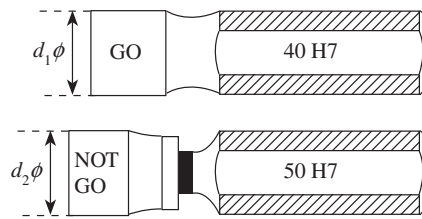


Fig. 3.31 Single-ended GO and NOT GO plug gauges

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.

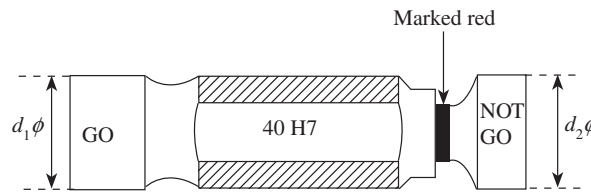


Fig. 3.32 Double-ended plug gauges

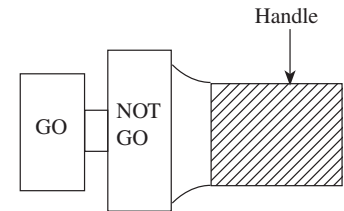


Fig. 3.33 Progressive plug gauges

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*

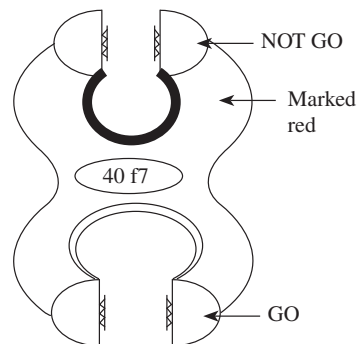


Fig. 3.34 Double-ended snap gauge

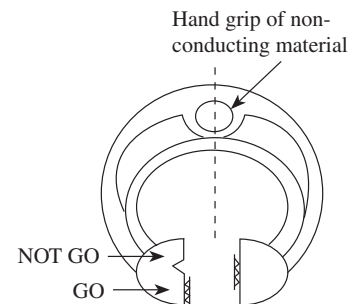


Fig. 3.35 Progressive snap gauge

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 permissible variation of dimension, or
Total variation permitted in the size. \Rightarrow the algebraic difference between upper & lower acceptable dim. always (+ve).

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

** Classification of tolerance :

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

$$\begin{matrix} +0.02 \\ +0.01 \end{matrix} / \begin{matrix} +0.02 \\ -0.00 \end{matrix} / \begin{matrix} -0.01 \\ -0.02 \end{matrix} / \begin{matrix} +0.00 \\ -0.02 \end{matrix}$$

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

3 Compound : more than one dimension.

4 Geometric : types : A Form : for individual Features, independent tolerance.

used to indicate the relationship of one part with another.

Ex: $L_A = 30 \begin{matrix} +0.02 \\ -0.01 \end{matrix}$, $L_B = 20 \begin{matrix} +0.02 \\ -0.01 \end{matrix}$, $L_C = 10 \begin{matrix} +0.02 \\ -0.01 \end{matrix}$

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

60 $\begin{matrix} +0.06 \\ -0.01 \end{matrix}$

* essential to avoid or minimize the cumulative effect of tolerance build-up

↳ by common reference line or base line

- Geometric characteristic : Straightness / Circularity / Flatness / Cylindricity.

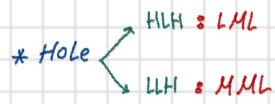
B Orientation : limit the direction or orientation, Related tolerance.

- Geometric characteristic : Perpendicularity / Parallelism / Angularity.

C Positional tolerance : controls the extent of deviation, Related Tolerance, 3D

- Geometric characteristic : Position (3D) / Symmetry (3D) / Concentricity (3D).

(3.4) Maximum & Minimum metal Conditions.



(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 : is the largest diameter of the shaft is smaller than the diameter of the smallest hole ?

min. dia. hole > max. dia. shaft

↓
easily assembled.

max. clearance : $HLH - LLS$

min. clearance : $LLH - HLS$

2 Interference Fit : is the minimum diameter of the shaft exceed the max. diameter of the hole ?

min. (shaft) > max. (hole).

↓
tight fit.

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

max. interference = $HLS - LLH$

min. interference = $LLS - HLH$

3 Transition : Largest hole > Smallest shaft

C. \rightarrow LML (hole) with LML (shaft) : clearance

smallest hole < Largest shaft.

I \rightarrow MML (hole) with MML (shaft) : interference.

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

Allowance = $LLH - HLS$

** Hole Basis sys. \rightarrow the fundamental deviation or lower deviation = Zero

$LLH = \text{Basic size}$ $E_L = \text{Zero}$

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

$HLS = \text{Basic size}$ $e_s = \text{zero}$

* Numerical Examples.

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

2 Hole = $25^{+0.03}_{+0.00}$, Shaft = $25^{-0.006}_{-0.02}$ \rightarrow 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 = $50^{-0.05}_{-0.08}$ \rightarrow 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 = $20^{+0.08}_{+0.005}$ \rightarrow Tolerance : hole = 0.025, shaft = 0.075

20.025 - hole 20.08 Shaft 20.005 \rightarrow transition fit. \Rightarrow HLH - LLS = +ve clearance
LLH - HLS = -ve interference \Rightarrow transition fit.

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

20.08 Shaft 20.06 hole 20.05 \rightarrow HLH - LLS = -ve
LLH - HLS = -ve \Rightarrow interference fit

(3.6) System of Limits & Fits :

$E_s = HLH - \text{Basic}$
 $E_I = LLH - \text{Basic}$ \Rightarrow Tolerance = HLH - LLH = $E_s - E_I$

$E_s = HLS - \text{Basic}$
 $E_I = LLS - \text{Basic}$ \Rightarrow Tolerance = HLS - LLS = $e_s - e_i$

① $\sqrt{D_1 \times D_2} = D$

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

③ Standard tolerance in $\mu\text{m} / 1000$.

Table (35) : $e_s(a) = E_I(A)$ the fundamental values.

(3.7) General terminology :

Basic size : size in relation to which all limit are derived. \rightarrow 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 \rightarrow difference between the max. & min. limits of size \rightarrow always (+ve).

Allowance : intentional difference between LLH & HLS \rightarrow 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

\rightarrow closest 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) \Rightarrow H8/f8.

□ for the Hole (H8) \Rightarrow table 3.5

\Rightarrow Basic size = 130 mm \Rightarrow 120-180 \Rightarrow $D_1 = 120$ $D_2 = 180$

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

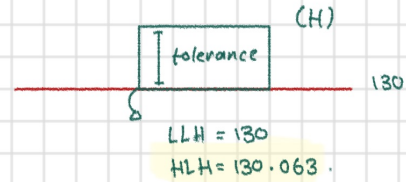
for hole \leftarrow $i = 0.45 (D)^{1/3} + 0.001 D \Rightarrow 0.45 (146.96)^{1/3} + (0.001 \times 146.96)$
 $= 2.52 \mu\text{m}$

\Rightarrow Find the tolerance: $IT_8 = 25 * i \Rightarrow 25 * (2.52) = 63.04 \mu\text{m} / 1000$
 $= 0.06304 \text{ mm}$
 hole tolerance

* Since f8 \Rightarrow IT8: then tolerance of

\rightarrow LLH = 130 $E_s = \text{Zero}$
 HLH = 130.063 $E_s = \text{HLH} - \text{Basic} = \text{tolerance}$
 $= 0.06304$

* The fundamental = $E_I = \text{Zero}$



\rightarrow For the Shaft:

$IT_8 = 0.06304$ from table 3.5 \Rightarrow The fundamental deviation e_s .

The fundamental is the upper deviation of the shaft.

$\leftarrow e_s = -5.5 D^{0.41} = -5.5 * (146.96)^{0.41}$, $e_s = -42.55 \mu\text{m}$
 $e_s = -0.04255 \text{ mm}$

$e_s = \text{HLS} - \text{Basic} \rightarrow -0.04255 = \text{HLS} - 130$

$\text{HLS} = 129.95745 \text{ mm}$

to find LLS: Tolerance = HLS - LLS

$-0.06304 = 129.95745 - \text{LLS}$

$\text{LLS} = 129.89445 \text{ mm}$

or Tolerance = $e_s - e_i$
 $= \text{HLS} - \text{LLS}$

ملاحظة الورد

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

from table 3.2 \Rightarrow loose fit = H8d9 \rightarrow 120-180.

Fundamental = lower value.

① for the hole : (H8)

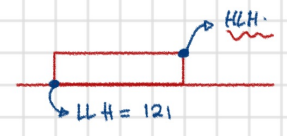
* $D = \sqrt{120 * 180} = 146.96 \text{ mm}$

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

*** $IT_8 = 25 (i) = 25 * 2.52 = 63.04 \mu\text{m} = 0.06304 \text{ mm}$ \rightarrow for the hole.

$IT_9 = 40 (i) = 40 * 2.52 = 100.8 \mu\text{m} = 0.1008 \text{ mm}$ \rightarrow for the shaft

H8 : $EI = \text{Zero}$ (fundamental).



from table 3.5 \rightarrow
 $E_s (\text{shaft}) = EI (\text{hole})$

E_s : Tolerance = $E_s - EI$ $E_s = 0.06304$

$HLH = LLH + \text{Tolerance} = 121.06304$

* $LLH = EI + \text{Basic}$

$HLH = 121.063 \text{ mm}$ LML
 $LLH = 120.00 \text{ mm}$ HML

② For the shaft (d9).

fundamental \leftarrow $E_s = -16 (D)^{0.44} = -16 * (146.96)^{0.44} = -143.77 \mu\text{m} = -0.143776 \text{ mm}$ \rightarrow from table 3.5.

Tolerance = $e_s - e_i \Rightarrow e_i = -0.143776 - 0.1008$

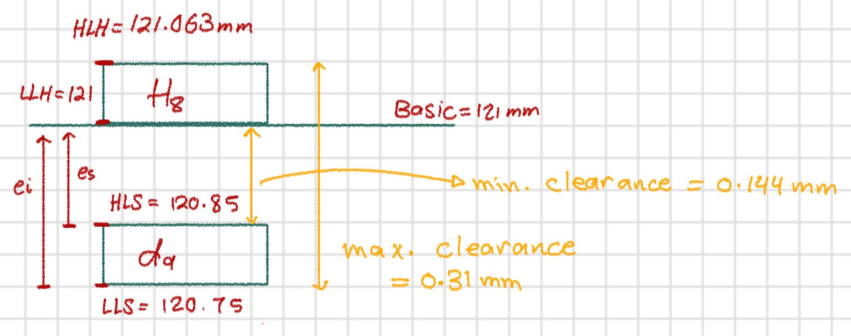
$e_i = -0.24457 \text{ mm}$

$e_i = LLS - \text{Basic} \Rightarrow LLS = -0.24457 + 121 = 120.75 \text{ mm}$ LML

$e_s = HLS - \text{Basic} = -0.143776 + 121 =$

$HLS = 120.856 \text{ mm}$ MML

سبب الجواب



Question 1

12 points

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

Given

The diameter steps are $D_1 = 80 \text{ mm}$, $D_2 = 120 \text{ mm}$

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

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

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

$$IT 6 = 10 * i$$

$$IT 7 = 16 * i$$

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

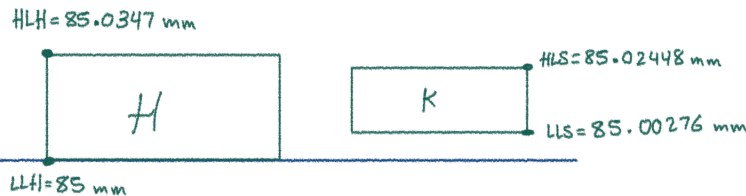
B. Draw a simple sketch for the shaft and hole system

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.



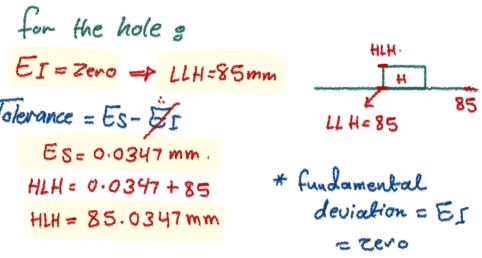
$$D = \sqrt{80 * 120} = 97.97 \text{ mm}$$

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

$$i = 2.172 \mu\text{m}$$

Tolerance, hole = 16 (i) = 34.76 μm
 = 0.0347 mm

shaft = 10 (i) = 0.02172 mm.



for the shaft

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

Tolerance = es - ei \Rightarrow es = 0.02172 + 0.00276

es = 0.02448 mm

es = HLS - Basic \Rightarrow HLS = 0.02448 + 85

HLS = 85.02448 mm

ei = LLS - Basic \Rightarrow LLS = 0.00276 + 85

LLS = 85.00276 mm

* The fundamental of the shaft = lower deviation = 0.00276

* أقرن ل Basic

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:

- Basic size
- Tolerances on shaft and hole
- Maximum and minimum clearances

$$* \text{Tolerance} = ES - EI$$

$$= \text{upper deviation} - \text{lower deviation}$$

$$\text{Hole} = 25^{+0.03}_{-0.00} \text{ mm}, \text{ Shaft} = 25^{-0.006}_{-0.020}$$

① Basic size = 25 mm

② Tolerance : shaft = $-0.006 - (-0.020) = 0.014$ mm
hole = 0.03 mm

③ Maximum & minimum clearance:

$$\text{Max. clearance} = HLH - LLS = 25.03 - 24.98 = 0.05$$

$$\text{Min. clearance} = LLH - HLS = 25.00 - 24.994 = 0.006$$

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.

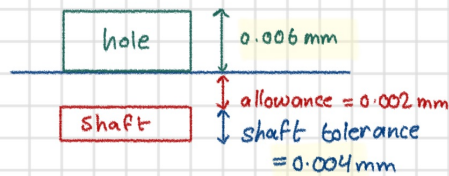
Basic = 40 mm ,

Tolerance : hole = 0.006 mm
Shaft = 0.004 mm

unilaterally

Allowance = 0.002 mm

a.) Hole basis sys.



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

$$\text{Allowance} = LLH - HLS = 0.002$$

* For the Hole :

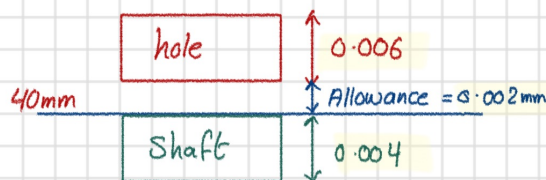
$$LLH = \text{Basic size} \Rightarrow \text{because it's hole basis system} = 40 \text{ mm}$$

$$HLH = \text{Basic} + \text{Tolerance} = 40.006 \text{ mm}$$

* For the Shaft :

$$HLS = LLH - \text{allowance} = 40 - 0.002 = 39.998 \text{ mm}$$

$$LLS = HLS - \text{Tolerance} = 39.998 - 0.004 = 39.994 \text{ mm}$$



b) Shaft basis system.

* For the Shaft :

$$HLS = 40 \text{ mm} \Rightarrow \text{Shaft basis sys.}$$

$$LLS = HLS - \text{Tolerance} = 40 - 0.004 = 39.996 \text{ mm}$$

* For the hole :

$$LLH - HLS = \text{Allowance} \Rightarrow LLH = 0.002 + 40 = 40.002 \text{ mm}$$

$$HLS = LLS + \text{Tolerance} = 39.996 + 0.006 = 40.002 \text{ mm}$$

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

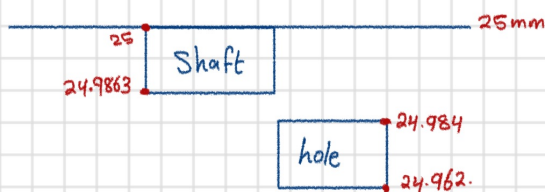
IT 7 = 16 * i

1. Calculate the following for both the shaft and the hole.

- Lower deviation
- Upper deviation
- Fundamental deviation
- Lower limit
- Upper limit
- Tolerance
- The minimum allowance
- The maximum allowance

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

* it's a shaft basis sys.



$$\text{Max. allowance} = LH - HLS = 24.962 - 25 = -0.038 \text{ mm}$$

$$\text{Min allowance} = HLH - LLS$$

$$D = \sqrt[3]{24 * 30} = 26.832 \text{ mm}$$

$$i = 0.45 (26.832)^{\frac{1}{3}} + 0.001 (26.832) = 1.374 \mu\text{m} = 0.001374 \text{ mm}$$

$$\text{Tolerance hole} = 16 * i = 0.0219 \text{ mm}$$

$$\text{Shaft} = 10 * i = 0.0137 \text{ mm}$$

$$\begin{aligned} \text{For the hole: } ES &= -5 (D^{0.34}) \\ &= -5 * (26.83)^{0.34} \\ &= -15.3 \text{ mm} \\ &= -0.0153 \text{ mm} \end{aligned}$$

$$ES = HLH - \text{Basic} \Rightarrow HLH = ES + \text{Basic}$$

↳ fundamental deviation \Rightarrow closer to the Basic.

$$HLH = 24.984 \text{ mm}$$

$$\text{Tolerance} = HLH - LLH \Rightarrow LLH = HLH - \text{tolerance}$$

$$LLH = 24.962 \text{ mm}$$

$$\text{Tolerance} = ES - EI \Rightarrow EI = ES - \text{Tolerance}$$

$$EI = -0.0372 \text{ mm}$$

For the Shaft:

$$es = \text{Zero} = \text{fundamental}$$

$$\text{Tolerance} = 0.0137 \text{ mm}$$

$$ei = es - \text{tolerance} = -0.0137 \text{ mm}$$

$$HLS = 25$$

$$LLS = HLH - \text{tolerance} = 24.9863 \text{ mm}$$

Shaft & hole system (25 H7/n6)

test a shaft \rightsquigarrow snap gauges
test a hole \rightsquigarrow plug //

$D_1 = 18 \text{ mm}, D_2 = 30 \text{ mm} \rightsquigarrow D = \sqrt{18 * 30} = 23.23 \text{ mm} \dots (1)$

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

$IT_7 = 16(0.001315) = 0.021 \text{ mm} \rightsquigarrow$ Tolerance of the hole.

$IT_6 = 10(0.001315) = 0.01315 \text{ mm} \rightsquigarrow$ Tolerance of the shaft. $\dots (3)$

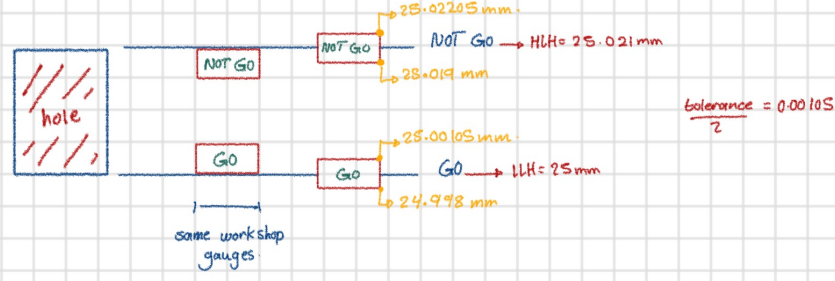
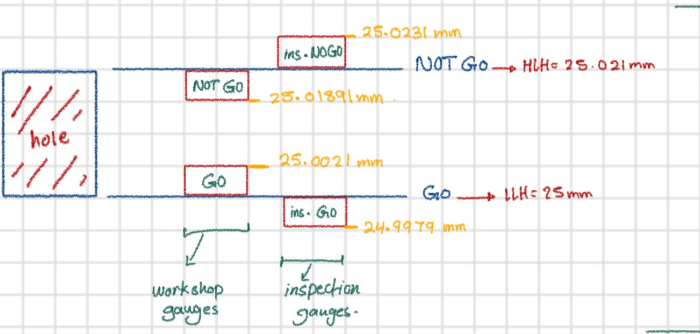
1 For the hole :

$EI = 0, LH = 25 \text{ mm}, HLH = 25.021 \text{ mm}, \text{ Tolerance} = 0.021 \text{ mm}$

Tolerance of the gauge (shaft) \rightsquigarrow 10% (hole tolerance) $= 0.1 * (0.021) = 0.0021 \text{ mm}$

1 Method one :

2 Revised method :

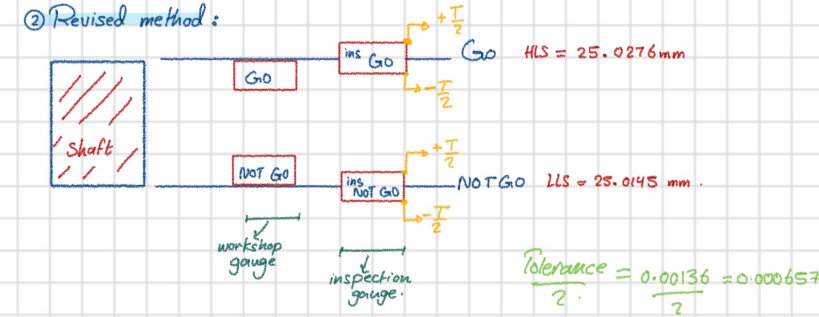
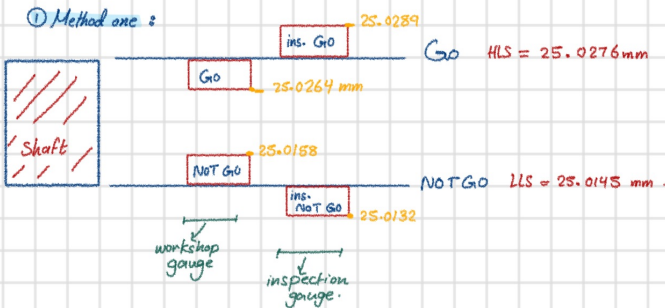


2 For the shaft (n6) :

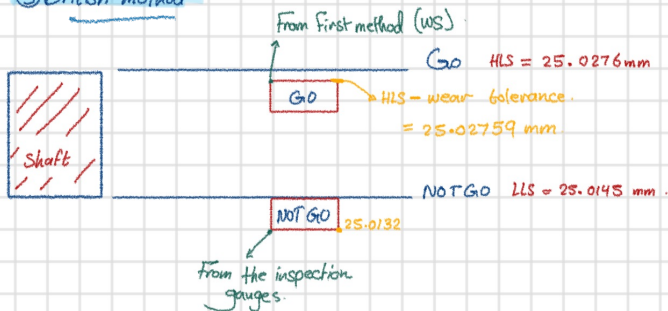
$e_i = 5(23.23)^{0.34} = 14.56 \mu\text{m} = 0.0145 \text{ mm} \rightsquigarrow$ LLS = 25.0145, Tolerance = 0.01315, Tolerance of the gauges = 0.001315 mm.
HLS = 25.0276 mm.

1 Method one :

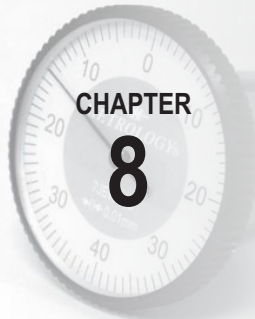
2 Revised method :



3 British method



* For the GO gauge \rightsquigarrow wear tolerance = 0.1 (gauge tolerance)
 $= 0.1(0.1 * \text{shaft tolerance})$
 $= 0.001316 \text{ mm}.$



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.

Gear: 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).

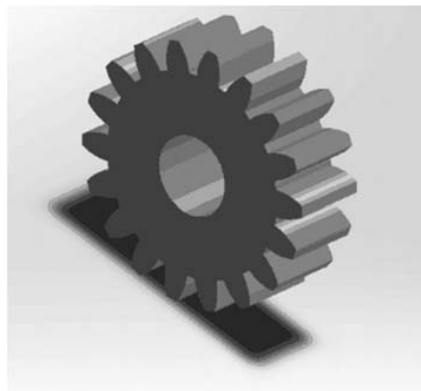


Fig. 8.1 Spur gear



Fig. 8.2 Herringbone gear

* Teams Links :

1 Gears : Types and its applications . → For heavy load applications .

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



Spur Gear



Helical Gear



Double Helical Gear (Herringbone Gear)



Bevel Gear

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

↳ two helical gears placed side by side.

↳ two non-parallel or intersecting



Worm Gear

→ to transmit power.
Worm gears : Screw thread.

one gear has screw thread ⇒ vibration free.

| Type | Spur | Bevel | | Worm | Hypoid | Helical |
|-------------------|----------------|--------------------|--------------------|--------------------------------------|--------------------------------------|----------------|
| | | Straight Bevel | Spiral Bevel | | | |
| | | | | | | |
| 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) : $module\ size = \frac{Diameter}{\#\ teeth + 2}$

For example :



30 teeth → $\frac{48}{30+2} = 1.5$

→ 30 teeth, 1.5 module gear.

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

* $\left(\frac{1\ inch}{25.4\ mm} \right)$; * $\left(DP = \frac{25.4}{module} \right)$
↳ pitch diamel

$\frac{25.4}{1.28} = 19.84\ DP$
 $1.28 = 20\ DP\ gear$

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

4:23
25-Dec.

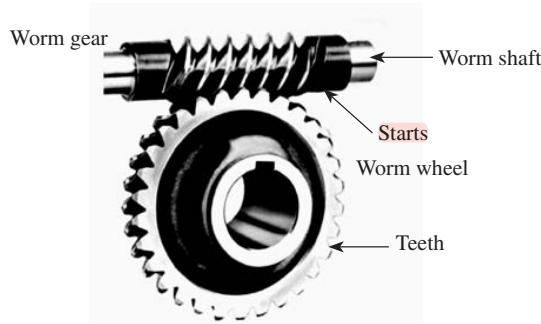


Fig. 8.3 Worm and worm gear



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.

When the rolling action will give the same rotation as an actual gear. with pitch diameter

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

Intersection for two gears.

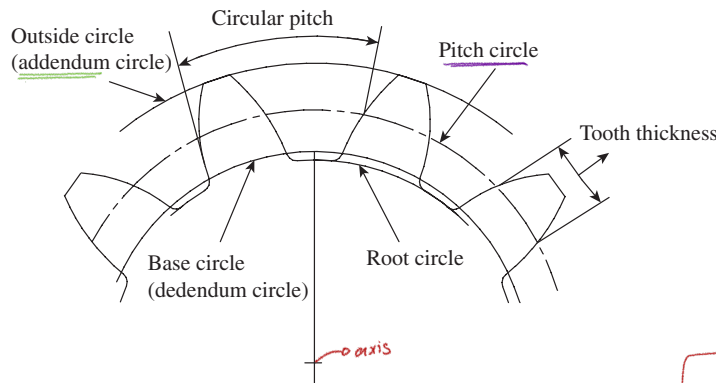


Fig. 8.5 Spur gear terminology

Total Depth = (Addendum + Dedendum) - in radial Direction.

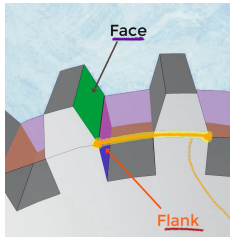
dedendum circle.

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.

also called Root circle.



Surface of the tooth above the pitch circle

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

Surface below the pitch circle.

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

Distance between a point on a tooth to the same point in the adjacent. (P_c)

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_o | $m(N + 2)$ |
| Root circle diameter | D_r | $D_o - 4.4m$ |
| Pressure angle | α | 20° or $14\frac{1}{2}^\circ$ |

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

$P_c = \frac{\pi * \text{Pitch Diameter}}{\# \text{ of teeth}}$

$P_D = \frac{\# \text{ of teeth}}{\text{Pitch diameter}}$

$\frac{\text{outside diameter}}{\# \text{ teeth} + 2} = \text{module size}$

around pitch



errors 2.

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.

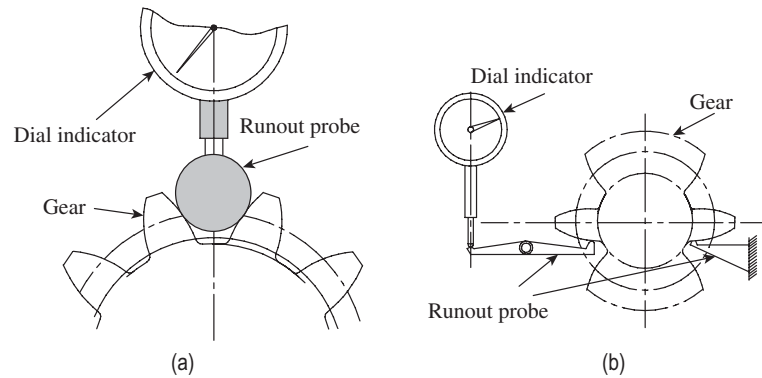


Fig. 8.7 Measurement of radial runout (a) Single-probe check (b) Two-probe check

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.

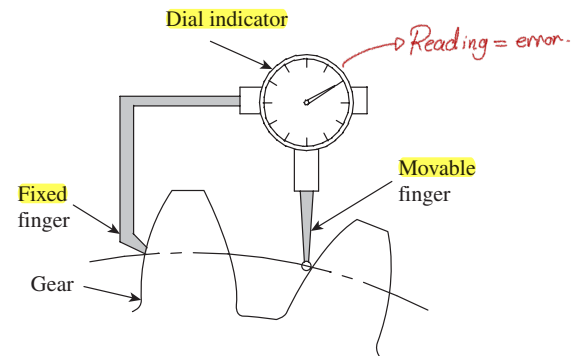


Fig. 8.8 Pitch-measuring instrument

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.

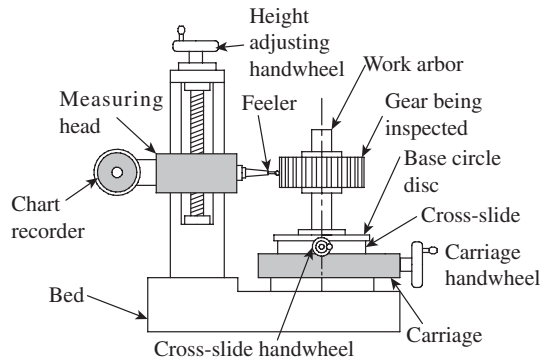


Fig. 8.11 Gear-measuring machine

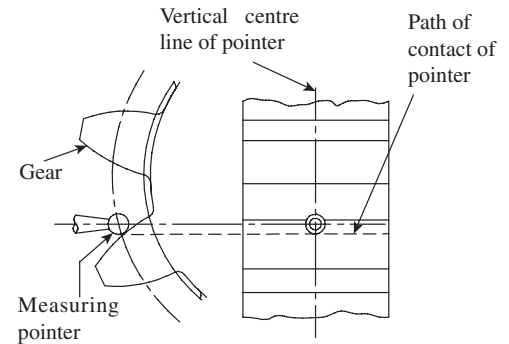


Fig. 8.12 Measurement of lead

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.

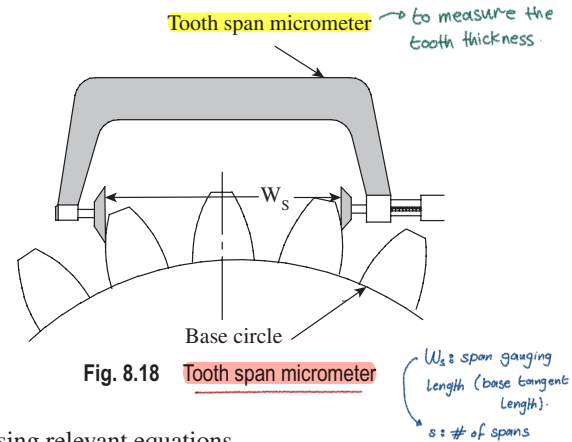


Table 8.3 Values of span width

| 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.

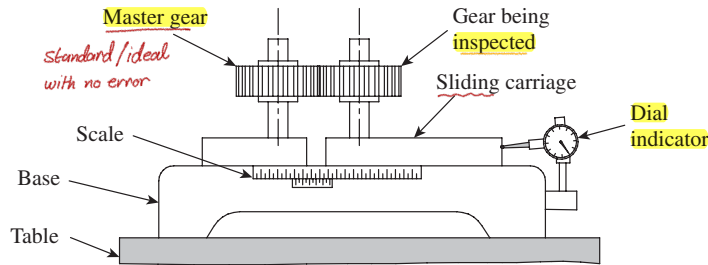


Fig. 8.19 Parkinson gear tester

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 $25\ \mu\text{m}$. 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

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.

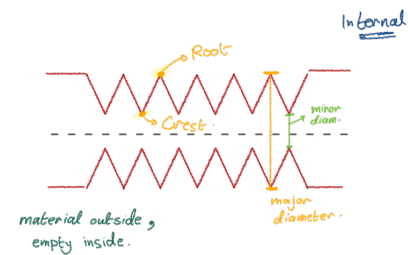
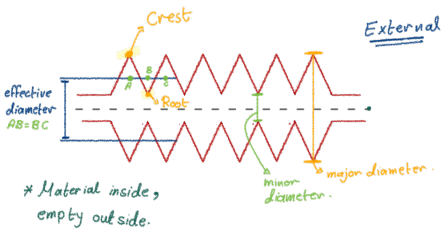
Axis of thread (pitch line) This is the imaginary line running longitudinally through the centre of the screw.

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.

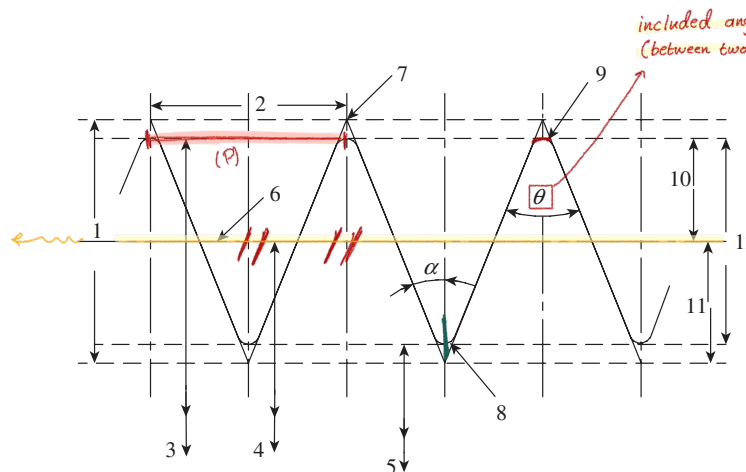
* External: cylindrical, on the outside diameter
 * Internal: nut, in the inner diameter of the cylindrical



* Root: groove between two Flank.
 * Flank: straight line connecting Crest with the root.

Effective (Pitch).

* P: from point to the same point in the next tooth
 - Root to Root
 - Crest to Crest
 - effective to effective.



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

radial distance

between the crest & Root & \perp to the axis.

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 screw 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. of 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 distance 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.

- * in micrometer :
 - Less accuracy
 - Less range \rightsquigarrow with fixed angle.
- * in Bench micrometers
 - accuracy up to (0.0002 mm)
 - wider range \rightsquigarrow two movable anvils.
- * using standard cylinder \rightsquigarrow



$$* \left(\text{Reading on the thread} \right) - \left(\text{Dia. of Thread} \right) = \left(\text{Reading on the cylinder} \right) - \left(\text{Dia. of cylinder} \right).$$

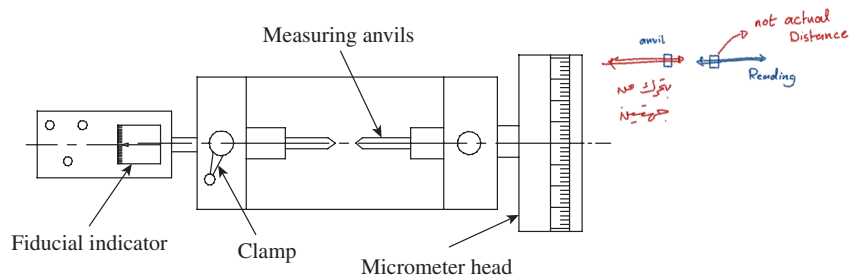
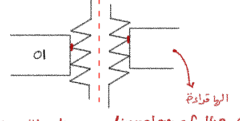


Fig. 8.21 Bench micrometer

accuracy \rightsquigarrow 0.0002mm

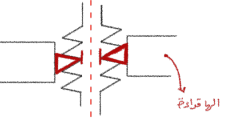
*** major diameter :**



* with known diameter of the cylinder (D_c)
 then take reading to the cylinder (R_c):
 $\rightarrow Error = R_c - D_c$
 $\rightarrow Error = R_{th} - D_{th}$ (unknown)

Example: $D_c = 10\text{mm}$, $R_c = 11\text{mm}$, $R_{th} = 13\text{mm}$
 $D_{th} = -(R_c - D_c) + R_{th} = -(1) + 13 = 12\text{mm}$

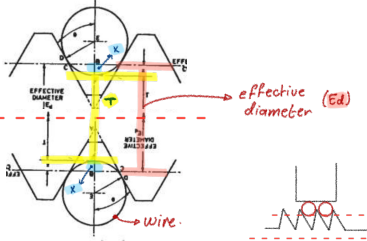
*** minor diameter :**



* used with prisms (accessory used with the Bench micrometer).

$$R_{th}(\text{prism}) - D_{th}(\text{minor}) = R_{prism} - D_c(\text{prism})$$

*** Effective diameter :**



* between the major & minor :
 * Distance between the wires (T).

$$R_m(\text{wire}) - T = R_c(\text{wire}) - D_c \quad \text{--- (1)}$$

$$2x = \frac{P}{2 \tan \theta} - d \left(\frac{1}{\sin \theta} - 1 \right) \quad \text{--- (2)}$$

$$D_E = T + 2x$$

* 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)

$$(R_{th} - D_{th} = R_c - D_c) \quad \text{or} \quad (R_{th} - R_c = D_{th} - D_c)$$

After rearrange the formula

$$\therefore \text{major } D_{th} = D_c + (R_{th} - R_c)$$

2. To find the **Minor diameter** of an external thread

$$\therefore \text{minor } D_{th} = D_c + (R_{th}(\text{prism}) - R_c(\text{prism}))$$

3. To find the **effective diameter** E_d of the external thread (using the three wires method)

For the distance T

$$T = D_c + (R_{th}(\text{wire}) - R_c(\text{wire}))$$

$$E_d = T + 2x$$

Where $2x = \frac{P}{2} \cot \theta - d(\text{cosec } \theta - 1)$

(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,

$$BC = \frac{1}{4} \text{ pitch} = \frac{1}{4} P$$

Therefore,

$$AB = \frac{1}{4} P \cot \theta$$

In the ΔADE ,

$$AE = DE \cos \text{ec } \theta = \frac{d}{2} \cos \text{ec } \theta$$

Now, $x = AB - AF$ and $AF = AE - EF = AE - d/2$

$$\therefore AF = \frac{d}{2} (\cos \text{ec } \theta - 1)$$

Therefore,

$$x = \frac{P}{4} \cot \theta - \frac{d}{2} (\cos \text{ec } \theta - 1)$$

where,

P = Nominal Pitch

D = Wire Diameter

θ = Nominal Flank Angle or semi angle of thread

$$* AF = AE - \frac{1}{2} d$$

$$AF = \frac{1}{2} d \left(\frac{1}{\sin \theta} - 1 \right)$$

$$* (x) = AB - AF$$

$$x = \frac{P}{4 \tan \theta} - \frac{d}{2} \left(\frac{1}{\sin \theta} - 1 \right)$$

$$2x = \frac{P}{2 \tan \theta} - d \left(\frac{1}{\sin \theta} - 1 \right)$$

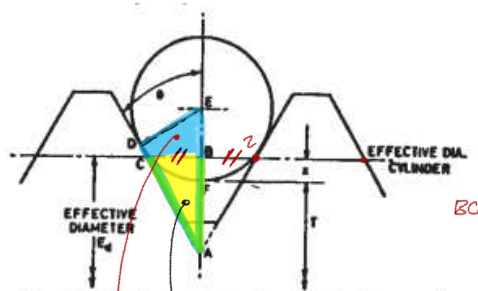


Fig-14 Calculation of simple effective diameter.

* crest to crest = Pitch dia.

$$BC = B_2 = \frac{1}{4} P$$

$$\tan \theta = \frac{BC}{AB} \Rightarrow AB = \frac{BC}{\tan \theta}$$

$$* BC = \frac{1}{4} (P)$$

$$AB = \frac{P}{4 \tan \theta}$$

$$\sin \theta = \frac{DE}{AE}$$

$$AE = \frac{DE}{\sin \theta}, \quad DE = \frac{1}{2} (\text{Diameter}) = \frac{1}{2} d$$

$$AE = \frac{d}{2 \sin \theta}$$

A. A bench micrometer was used to measure the dimensions for an external thread; the readings are given as:

$$\text{The reading over the thread} = 20.6278 \text{ mm}$$

$$\text{The reading over the cylinder} = 20.7166 \text{ mm}$$

$$\text{The reading over the thread (with wires)} = 21.0814 \text{ mm}$$

$$\text{The reading over the cylinder (with wires)} = 24.2788 \text{ mm}$$

$$\text{The reading over the thread (with prisms)} = 22.9336 \text{ mm}$$

$$\text{The reading over the cylinder (with prisms)} = 26.5414 \text{ mm}$$

And you know that the diameter of the standard cylinder is equal to 20 mm, the flank angle of the thread (θ) = 30° , 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)

$$\begin{aligned} \boxed{1} D_{\text{major}} &= D_c + (R_{\text{th}} - R_c) \\ &= 20 \text{ mm} + (20.6278 - 20.7166) = 19.9112 \text{ mm} . \end{aligned}$$

$$\begin{aligned} \boxed{2} D_{\text{minor}} &= D_c + (R_{\text{th}(p)} - R_{\text{c}(p)}) = \\ &= 20 \text{ mm} + (22.9336 - 26.5414) = 16.3922 \text{ mm} . \end{aligned}$$

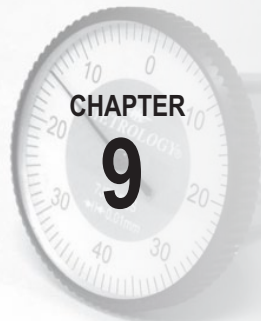
3 Effective :

$$\begin{aligned} \textcircled{1} \text{ to find } T \Rightarrow T &= D_c + (R_{\text{th}(w)} - R_{\text{c}(w)}) = 20 + (21.0814 - 24.2788) \\ &= 16.8026 \end{aligned}$$

$$\begin{aligned} \textcircled{2} 2x &= \frac{p}{2 \tan \theta} - d \left(\frac{1}{\sin \theta} - 1 \right) = \frac{3.5}{2 \tan(30^\circ)} - 2.0207 \left(\frac{1}{\sin 30} - 1 \right) \\ &= 1.0104 \text{ mm} \end{aligned}$$

$$\rightarrow D_{\text{eff}} = T + 2x = 16.8026 + 1.0104 = 16.813 \text{ mm} .$$

Handwritten signature



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.

Smooth 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.

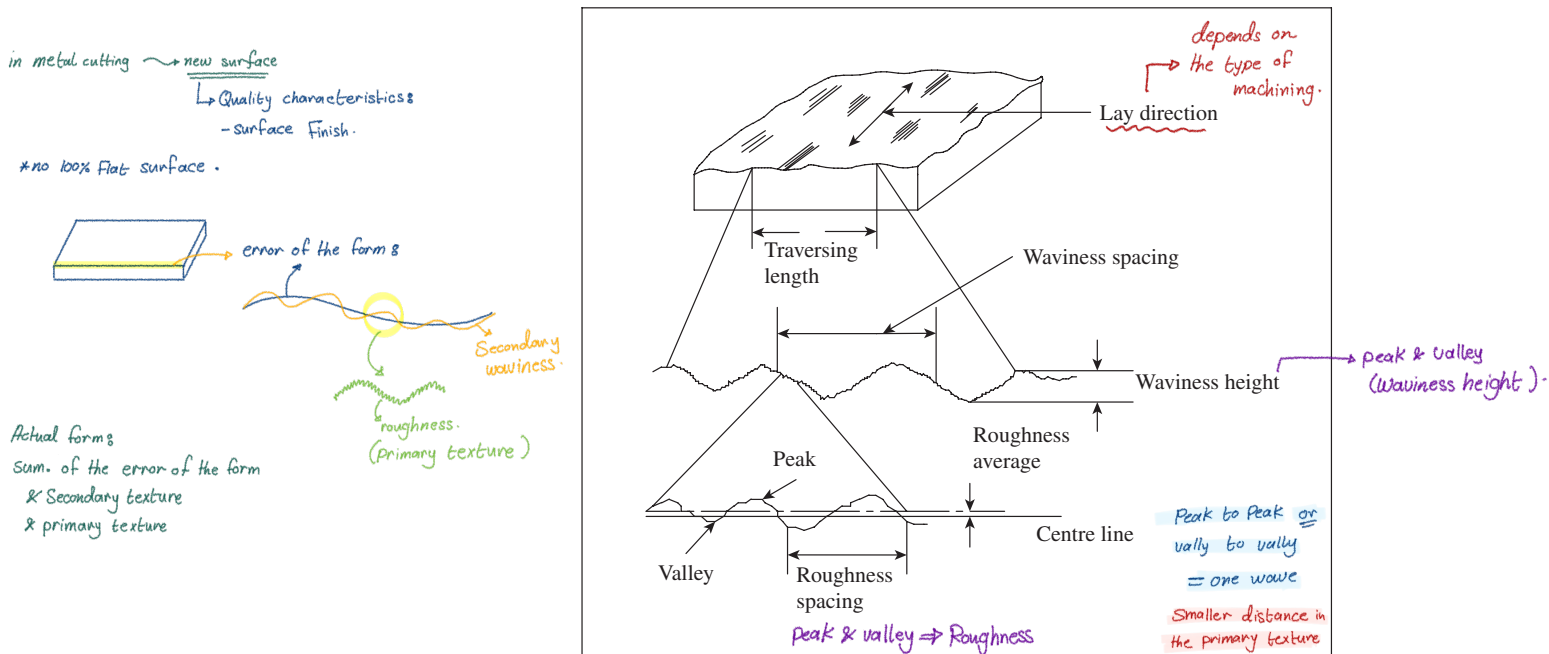


Fig. 9.1 Waviness and roughness

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.

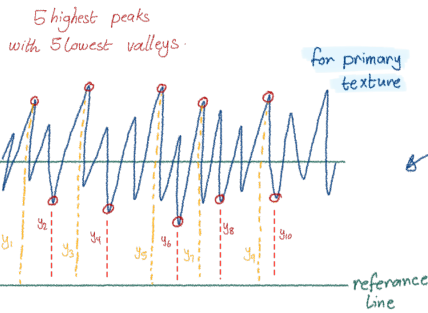
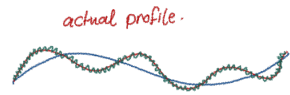
Surface texture It is generally understood as the repetitive or random deviations from the nominal surface that form the pattern of the surface. Surface texture encompasses roughness, waviness, lay, and flaws.

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.

Error of the form (wider)
 ↓
 Waviness (Secondary)
 ↓
 Roughness (Primary)

9.4 ANALYSIS OF SURFACE TRACES (Quantitative technique).

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:

$$R_z = \frac{(h_1 + h_3 + h_5 + h_7 + h_9) - (h_2 + h_4 + h_6 + h_8 + h_{10})}{5} \times \frac{1000}{\text{Vertical magnification}} \mu\text{m}$$

↙ average distances between peaks & valleys

* هون كان القياس ب (cm) وانا بيري ايام ب (mm) ليه بولها والقياس ليس جزء منه القاون

1 cm = 10000 μm
1 mm = 1000 μm
1 m = 1000000 μm

Ten-point technique is not representative to the whole profile base on highest & lowest point.

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, \dots, h_n are equally spaced ordinates at points 1, 2, ..., n, then

$\sqrt{\frac{\sum h_i^2}{n}}$ = average for the square values.

$$RMS = \sqrt{\frac{\sum h_i^2}{n}} \times \frac{1}{VMF}$$

* higher value of (n) ⇒ more accurate value.
 $0 < n < \infty$

$$h_{RMS} = \sqrt{\frac{(h_1^2 + h_2^2 + \dots + h_n^2)}{n}}$$

هاد خط

* Center Line Average Value

All areas above & below the mean line with (+ve) sign total length

= average distance for all point & mean line.

$$\frac{\sum A}{L} \times \frac{1}{VMF}$$

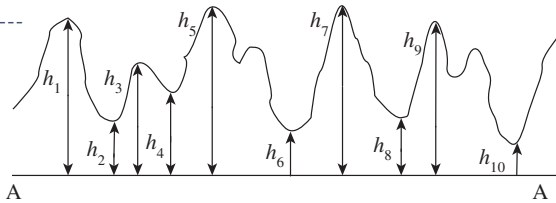


Fig. 9.2 Measurement to calculate the 10-point height average

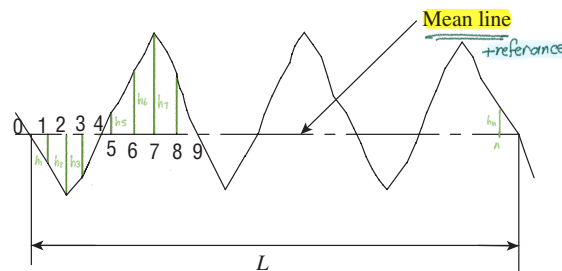


Fig. 9.3 Representation of an RMS value

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

$$Ra = \frac{A_1 + A_2 + \dots + A_N}{L} = \frac{\sum A}{L}$$

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 \Rightarrow All (+ve)

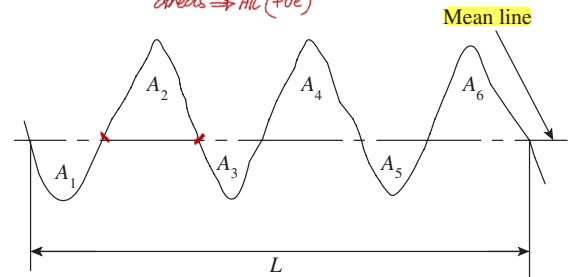


Fig. 9.4 Representation of Ra value

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 \Rightarrow depends on the process -
* process parameter

| Process | Ra value in micrometres | | | | | | |
|-----------------|-------------------------|----------------------|----------------------|----------------------|-------|----------|-----------|
| | 50-25 | 25-10 | 10-2.5 | 2.5-1 | 1-0.2 | 0.2-0.05 | 0.05-0.01 |
| Flame cutting | ████████████████████ | | | | | | |
| Sawing | ████████████████████ | | | | | | |
| Drilling | | | ████████████████████ | | | | |
| Milling | | ████████████████████ | | | | | |
| Reaming | | | ████████████████████ | | | | |
| Laser machining | | | ████████████████████ | | | | |
| Grinding | | | ████████████████████ | | | | |
| Lapping | | | | ████████████████████ | | | |
| Sand casting | ████████████████████ | | | | | | |
| Forging | | ████████████████████ | | | | | |

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

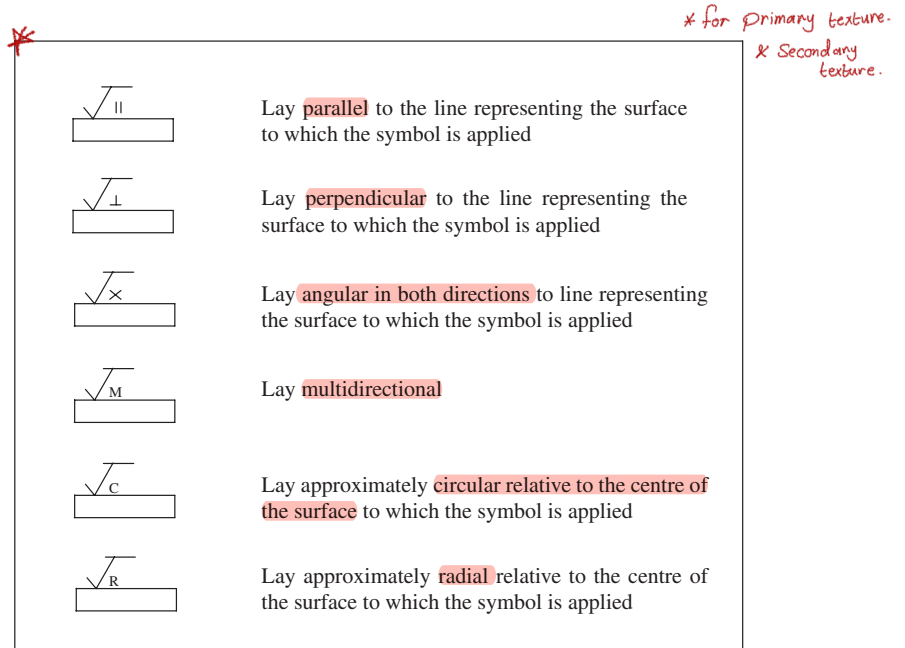


Fig. 9.6 Symbolic representation of the various types of lays of a surface texture

11:15
26-Dec.

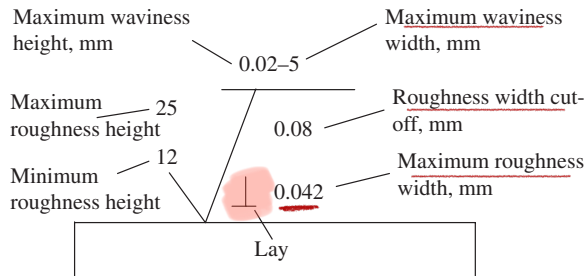


Fig. 9.7 Surface texture symbols

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

device with stylus ⇒ actual profile + value

Primary technique : (comparison)
 quantitative technique to compare
 different w.p
 * not exact value to the roughness,
 only comparison.
 * using a gauge (Robert gauge)
 ↳ standard gauge
 ⇒ compare by feeling of the surface.
 * not accurate technique.
 So we use the stylus ⇒
 draws actual profile so
 I can use the quantitative
 technique.

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

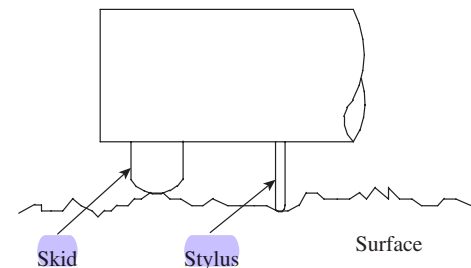
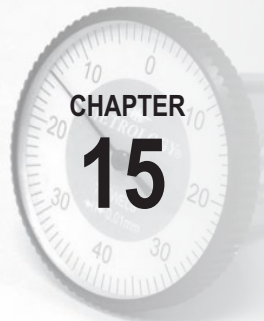


Fig. 9.8 Skid and stylus type



Measurement of Temperature

X

**indirect measuring device.*

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 |

$$\frac{F - 32}{212 - 32} = \frac{C - 0}{100 - 0}$$

$$\frac{F - 32}{180} = \frac{C}{100} \Rightarrow C = \frac{(F - 32) \cdot 100}{180}$$

$$= (F - 32) / 1.8$$

The scales used to measure temperature can be divided into relative scales [Fahrenheit ($^{\circ}\text{F}$) and Celsius ($^{\circ}\text{C}$)] and absolute scales [Rankine ($^{\circ}\text{R}$) and Kelvin (K)]. The various temperature scales are related as follows:

$$\begin{aligned} \checkmark F &= 1.8C + 32 \\ \checkmark C &= (F - 32) / 1.8 \\ R &= F + 460 \longrightarrow \text{linear} \\ \checkmark K &= C + 273 \longrightarrow \text{linear} \end{aligned}$$

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

made from 2 different types of metal (at least):

15.3 THERMOCOUPLES *contact measuring device:*

** When there is heating \rightarrow 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.

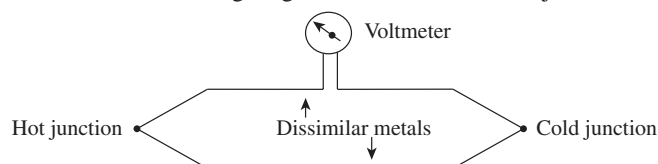


Fig. 15.1 Basic thermocouple circuit

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;

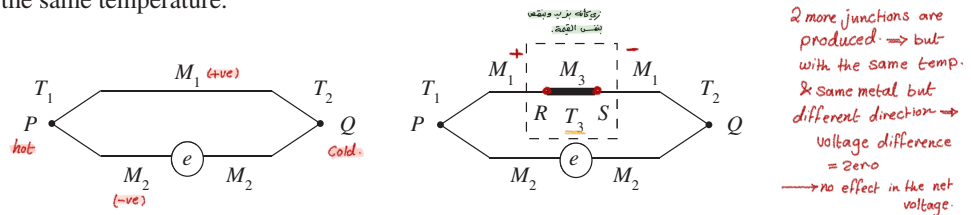


Fig. 15.2 Law of intermediate metals

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.

e_1 : difference in voltage from the cold junction & hot junction.

→ if cold junction = zero
voltage in hot junction = Reading of voltmeter (E_i)

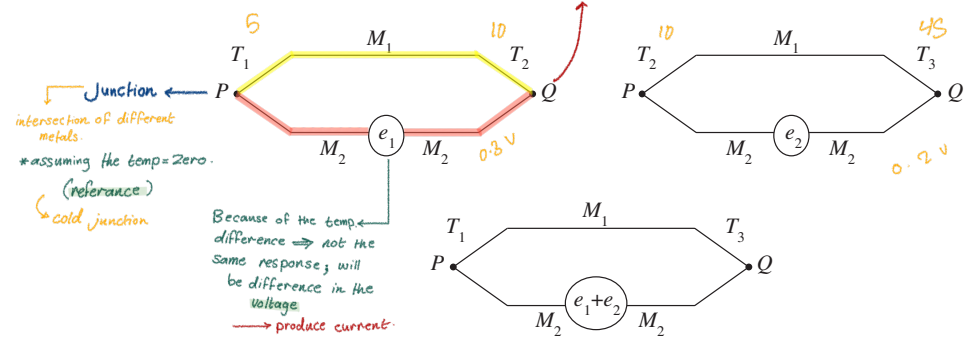


Fig. 15.3 Law of intermediate temperatures

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

* depends on the type of metal
* temp. on the hot junction increase, the difference in voltage will increase. (temp-voltage relationship).



| Type | Thermocouple materials | Temperature range (°C) |
|------------------------|--|------------------------|
| <u>Base metal type</u> | | |
| 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) <i>2 alloys.</i> | -200 to 1300 |
| <u>Rare metal type</u> | | |
| S | Platinum (90%)—rhodium— <u>platinum</u> (10%) | 0-1500 |
| R | <u>Platinum</u> —rhodium (87% Pt, 13% Rh)—platinum | 0-1500 |

in case cold junction = 0.

wider ranges

for higher temp because of platinum.

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

| °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 |

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 |

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 |

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.

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

$$\frac{T - 272}{273 - 272} = \frac{14.82 - 14.776}{14.831 - 14.776}$$

- (J) table
- $V_{\text{cold}} = 0^\circ$
- $V_{\text{Reading}} = V_{\text{hot}}$
- Reading = 14.82

| 272° | 273° |
|--------|--------|
| 13.666 | 13.722 |
| 14.221 | 14.277 |
| 14.776 | 14.831 |
| 15.330 | 15.386 |

interpolation:

$$\frac{14.831 - 14.776}{14.831 - 14.82} = \frac{273 - 272}{273 - x}$$

$$x = \underline{\underline{272.8}}$$

* Interpolation \rightarrow Assuming linear relationship in a small range.

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 $\neq 0$

$$V_{(\text{hot})} = \underline{V_{(\text{cold})}} + \text{Reading.}$$

from (J) table with 25°
V = 1.277 mv.

| | |
|-------|--------|
| 4.672 | 89 |
| 4.721 | T = ?? |
| 4.726 | 90 |

$$V_{(\text{hot})} = 1.277 + 3.444 = \underline{4.721}$$

| | | | |
|---------|-------|----|---|
| } 3.596 | 3.650 | 60 | * interpolation even if the relation is non-linear. |
| } 4.133 | 4.187 | 70 | |
| } 4.672 | 4.726 | 80 | |
| } 5.215 | 5.269 | 90 | |

T = 89.907 c

for interpolation =

$$\frac{4.726 - 4.672}{4.726 - 4.721} = \frac{90 - 89}{90 - x}$$
$$= 89.907 \text{ C}$$



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.

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.

Expensive if it's made from platinum.

RTD: Linear
Thermistor: exp.
Thermocouple: non-linear (Cables).

تلوث

✗ 15.3.4 Thermopiles

An extension of thermocouples is known as a thermopile. A thermopile comprises a number

Thermistor
RTD
Thermocouple

↑ more sensitivity.

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 $1\text{ mV}/^\circ\text{C}$ 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.

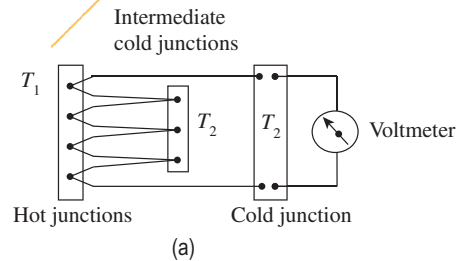


Fig. 15.4 Thermopiles (a) Series connection (b) Star connection

Reading = value of Resistance

then find the relationship between Resistance & Temp.

** electrical resistance change with changing the temp.*

15.4 RESISTANCE TEMPERATURE DETECTORS

contact measuring device.

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**

المفروض انهم
مش لاحظت بس
الصحيح.

following factors:

مش كثير يتفاعل
كيميائياً

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**.

ترادف

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

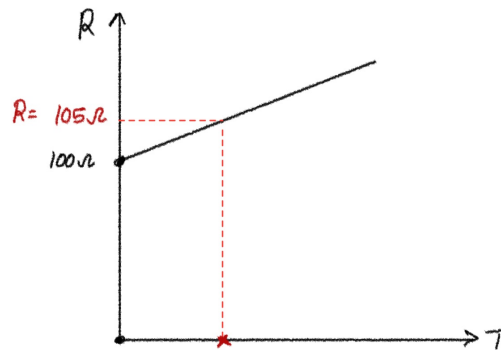
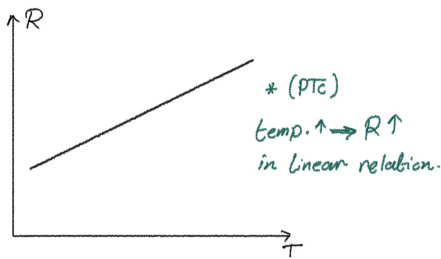
مس لفظ

$$T = \frac{R_0 - R}{-0.5(R_0 A + \sqrt{R_0^2 A^2 - 4R_0 B(R_0 - R)})}$$

* will give temp. in C°.

Where :

- depend in type of RTD ← T : Calculated temperature in (°C).
- R_0 : RTD nominal resistance at 0 °C, $R_0 = 100 \Omega$.
- R : Measured resistance (Ω).
- Constant depend in the type of metal. $A = 3.90802 \times 10^{-3}$
- $B = -5.80195 \times 10^{-7}$



$$R = R_0(1 + \alpha \cdot \Delta T)$$

measured ← R → 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.

المغزى انه
صحيح

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 $\pm 0.1^\circ\text{C}$). Standard **platinum** resistance thermometers have ultra-high accuracy of around $\pm 0.0001^\circ\text{C}$.
3. They have excellent **stability** over time.

Should be ductile
to form as wire

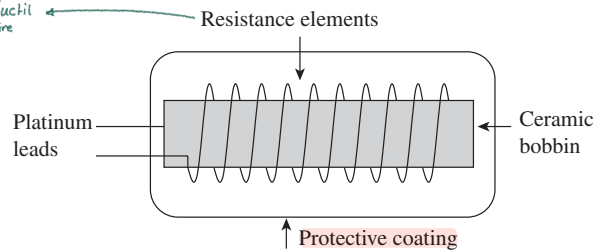


Fig. 15.5 Wire-wound RTD

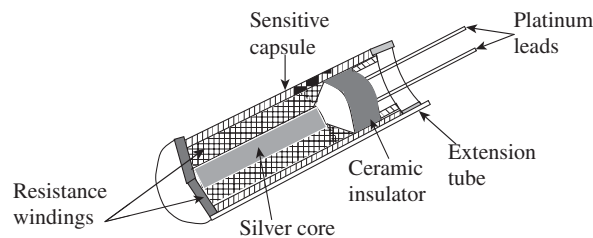


Fig. 15.6 General construction of an RTD

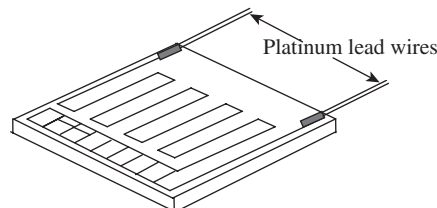


Fig. 15.7 Thin film RTD

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 \longrightarrow contact measuring device

* more sensitive than (RTD)

يكونه في التغير كبير
نقطة المقاومة صفر
التغير الـ temp ان قليل

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.**

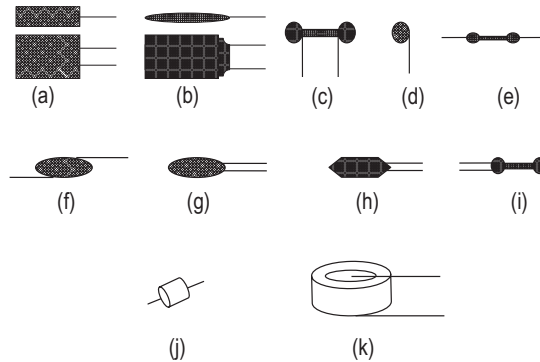


Fig. 15.8 Different forms of thermistors (a, b) Wafers (c–e) Rods (f–i) Beads (j, k) Disks

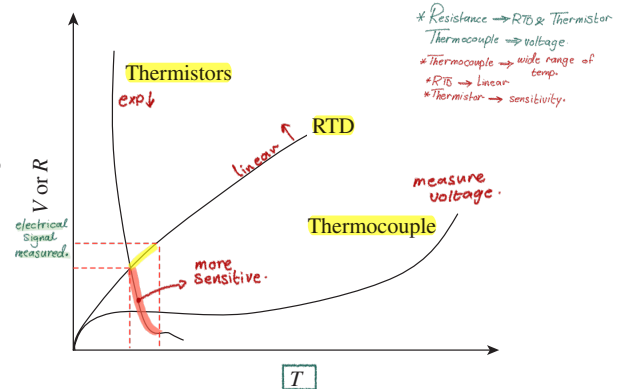


Fig. 15.9 Comparison of temperature characteristics

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

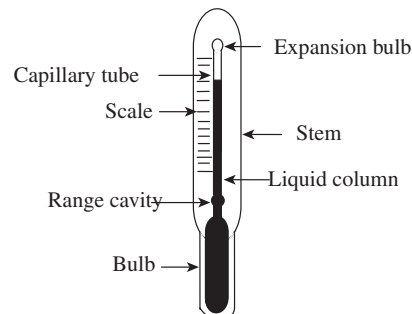


Fig. 15.10 Liquid-in-glass thermometer

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.

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

$$T = \frac{1}{a + b(\ln R) + c(\ln R)^3}$$

Where :

T : Calculated temperature in (K)

R : Measured resistance in (Ω)

a , b and c are Steinhart-Hart Constants that have the following values

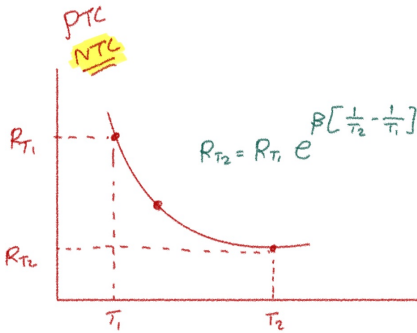
$$a = 1.2407635 \cdot 10^{-3}$$

$$b = 2.3612017 \cdot 10^{-4}$$

$$c = 8.97975 \cdot 10^{-8}$$

Constant, depend
in the type of
material.

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

لازم على الأصل
3 نقاط

* NTC / PTC
↳ most used.
↳ Temp ↑ → R ↓

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 ($^{\circ}\text{K}$) can be represented by the following relationship for most of the metals as :

$$R = R_0 (1 + \alpha_1 T + \alpha_2 T^2 + \dots + \alpha_n T^n + \dots) \quad \dots(5.55)$$

where R_0 = resistance at temperature $T = 0$ and $\alpha_1, \alpha_2, \alpha_3, \dots, \alpha_n$ 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 proffered 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.

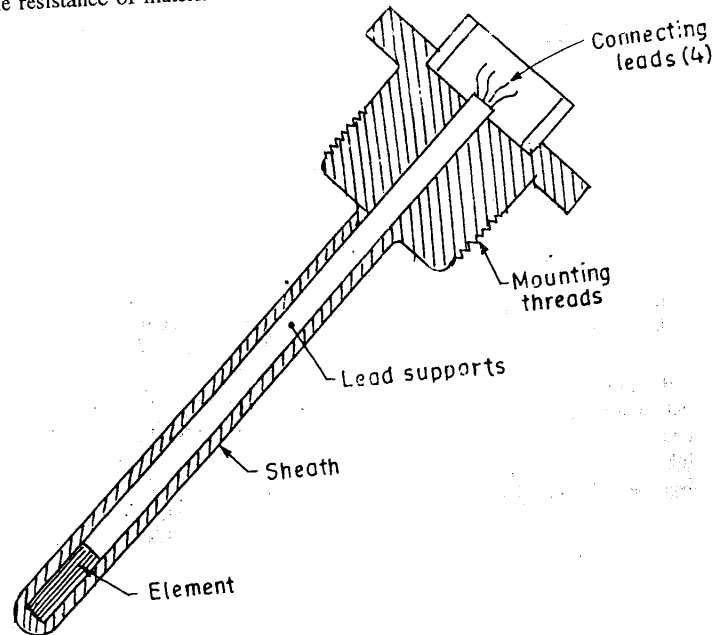


Fig. 5.40. Industrial platinum resistance thermometer.

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 bead 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.

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. In 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 :

$$R_\theta = R_{\theta_0} (1 + \alpha_{\theta_0} \Delta\theta) \text{ with } \theta_1 < \theta_0 < \theta_2 \quad \dots(5.56)$$

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,

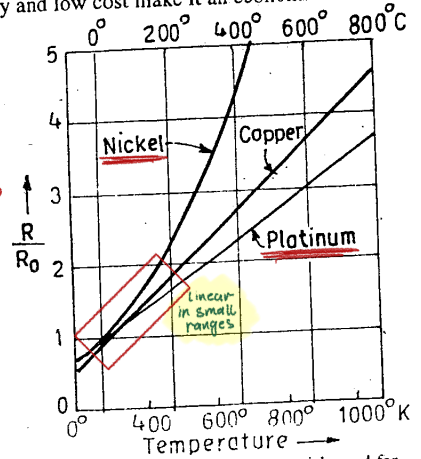


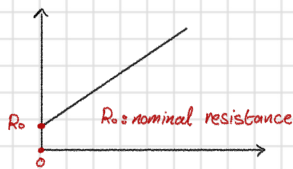
Fig. 5.41. Characteristics of materials used for resistance thermometers.

$R_0 = 100 \Omega$ (platinum)
when temp = 0
1. Linear
2. Sensitive

↳ range up to 200°C

pure $\Rightarrow \alpha \uparrow$

① RTD: electrical resistance changes with changing the temp. — Linearly, PTC.



* $\frac{R}{R_0} = (1 + \alpha_1(T - T_0) \dots)$

* the change in resistance can be given by:

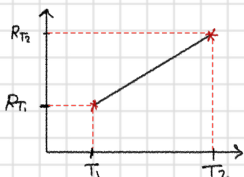
$R = R_0(1 + (\alpha_1 T) + (\alpha_2 T^2) + \dots + (\alpha_n T^n))$ → polynomial
 * General formula

** $R = R_0(1 + \alpha(T - T_0) + \alpha_2(T - T_0)^2 \dots)$

→ 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 → بين 0 إلى 200 درجة حرارة



$\alpha = \frac{1}{R_0} \left(\frac{\Delta R}{\Delta T} \right)$, $R = R_0(1 + \alpha_1(T - T_0) + \alpha_2(T - T_0)^2 \dots)$
 case (1) [Linear] case (2) [Quadratic]

* بتاي الالة رج العمل
 متادلية

رج احصيا قيمة بناءً على
 النقام الي عندي

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 :

$\theta_1 = 100^\circ\text{C}, \theta_2 = 130^\circ\text{C}, \theta_0 = 115^\circ\text{C}$

$R_{\theta_1} = 573.40 \Omega, R_{\theta_2} = 605.52 \Omega, R_{\theta_0} = 589.48 \Omega$

هذا ما اعطى قيمة (R)
 متوسط $\frac{R_2 + R_1}{2}$

* About nominal (mean) temp. 115°

$R_0 = 589.48$, (mid point).

$T_1 = 100^\circ\text{C}$

$T_2 = 130^\circ\text{C}$

$T_0 = 115^\circ\text{C}$

$\alpha = \frac{\text{slop}}{R_0} = \frac{1}{R_0} \left(\frac{\Delta R}{\Delta T} \right)$

1 Linear :

$\alpha = \frac{1}{R_0} \left(\frac{R_2 - R_1}{T_2 - T_1} \right) = \frac{1}{589.48} \left(\frac{605.52 - 573.4}{130 - 100} \right)$

$\alpha = 0.00182 \text{C}^{-1}$ around mid point 115°C

$R = R_0(1 + \alpha(T - T_0))$

$R = 589.48 (1 + 0.00182(T - 115))$

* $\frac{1}{C}$ 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 :

$R = R_0(1 + \alpha_1(T - T_0) + \alpha_2(T - T_0)^2)$

→ for 100°C :

$573.40 = 589.48 (1 + \alpha_1(100 - 115) + \alpha_2(100 - 115)^2)$
 $\frac{573.40}{589.48} - 1 = -15\alpha_1 + 15^2\alpha_2 \dots \textcircled{1}$

→ for 130°C :

$605.52 = 589.48 (1 + \alpha_1(130 - 115) + \alpha_2(130 - 115)^2)$
 $\frac{605.52}{589.48} - 1 = 15\alpha_1 + 15^2\alpha_2 \dots \textcircled{2}$

$-0.02727 = -15\alpha_1 + 225\alpha_2$

$0.02721 = 15\alpha_1 + 225\alpha_2$

$-0.05448 = -30\alpha_1 \rightarrow \alpha_1 = 1816 \times 10^{-3}$

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.

Quadratic $R = R_0 [1 + \alpha_1(T - T_0) + \alpha_2(T - T_0)^2]$
 $573.40 = 589.48 [1 + \alpha_1(100 - 115) + \alpha_2(100 - 115)^2]$ --- (1)

1. Linear Expansion : Given :

$\theta_1 = 100^\circ\text{C}, \theta_2 = 130^\circ\text{C}, \theta_0 = 115^\circ\text{C}$
 $R_{\theta_1} = 573.40 \Omega, R_{\theta_2} = 605.52 \Omega, R_{\theta_0} = 589.48 \Omega$

From Eqn. 5.57,
 $573.40 = 589.48 [1 + \alpha_1(100 - 115) + \alpha_2(100 - 115)^2]$ --- (1)
 $573.40 - 589.48 = -18.08\alpha_1 + 15\alpha_2$ --- (1)
 $605.52 = 589.48 [1 + \alpha_1(130 - 115) + \alpha_2(130 - 115)^2]$ --- (2)
 $605.52 - 589.48 = 15.04\alpha_1 + 15\alpha_2$ --- (2)

From Eqn. 5.57,

$\alpha_{\theta_1} = \alpha_1 = \frac{1}{R_{\theta_0}} \times \frac{R_{\theta_2} - R_{\theta_1}}{\theta_2 - \theta_1}$
 $= \frac{1}{589.48} \times \frac{605.52 - 573.40}{130 - 100} = 0.00182 / ^\circ\text{C}$

\therefore The linear approximation is :

$R_\theta = 589.48 [1 + 0.00182 (\theta - 115)] \Omega.$

2. Quadratic Expansion : The resistance R_θ at any temperature $\theta^\circ\text{C}$ 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

$\theta_0 = 115^\circ\text{C}.$

We have,

$R_{\theta_0} = 589.48 \Omega$ at $\theta_0 = 115^\circ\text{C}.$

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,

$\alpha_1 = 1.823 \times 10^{-3} / ^\circ\text{C}$ and $\alpha_2 = -0.22 \times 10^{-6} / (^\circ\text{C})^2$

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 $\theta^\circ\text{C}$, is

$R_\theta = R_{\theta_0} [1 + \alpha_{\theta_0} \Delta\theta]$

\therefore Resistance at 65°C is,

$R_{65} = 100 [1 + 0.00392 (65 - 25)]$
 $= 115.68 \Omega.$

(b) Suppose θ is the unknown temperature,

$150 = 100 [1 + 0.00392 (\theta - 25)]$
 $\theta = 152.55^\circ\text{C}.$

or

Example 5.19. A copper resistor at 20°C is to be 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.

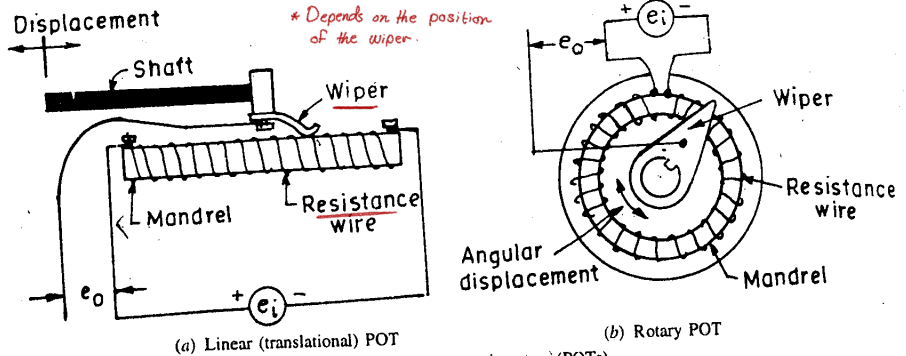


Fig. 5.24. Resistive potentiometers (POTs)

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 **helipot**.

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 **helipot**.

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).

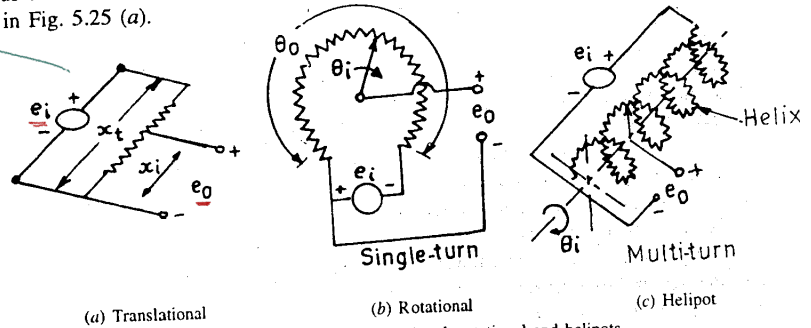


Fig. 5.25. Diagrams for translational, rotational and helipot.

voltage division device

$V_o = V_{in} \cdot \frac{x_i}{x_t}$
 حيث ان x_i هي موضع الويبر من طرف اليمين و x_t هي المقاومة الكلية.
 وهي قيمة ثابتة لا تتغير مع التغير في قطر الويبر.

* assuming that the resistance of Reading device = ∞ .

$\frac{e_o}{e_i} = \frac{x_i}{x_t}$ → ideal case (resistance of measuring device = ∞).
 R_p : Total Resistance.
 $e_o = \frac{x_i}{x_t} e_i$, $e = RI$ →
 $R \cdot I = \left(\frac{x_i}{x_t}\right) R_p \cdot I \rightarrow R = \left(\frac{x_i}{x_t}\right) R_p$
 assuming constant current

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 :

$$e_o = \left(\frac{\text{resistance at the output terminals}}{\text{resistance at the input terminals}} \right) \times \text{input voltage}$$

$$= \left[\frac{R_p(x_i/x_t)}{R_p} \right] e_i = \frac{x_i}{x_t} \times e_i \quad \dots(5.28)$$

Under the ideal circumstances, the output voltage varies linearly with displacement as shown in Fig. 5.26 (a).

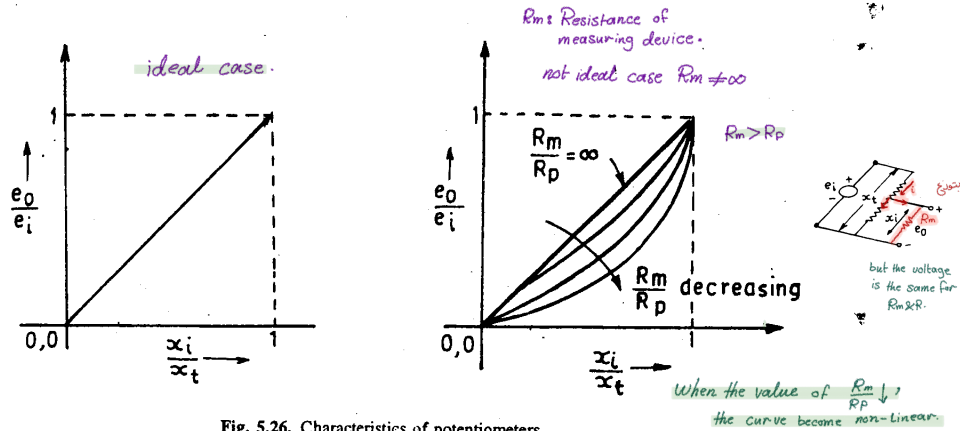


Fig. 5.26. Characteristics of potentiometers.

Sensitivity $S = \frac{\text{output}}{\text{input}} = \frac{e_o}{x_i} = \frac{e_i}{x_t} \quad \dots(5.29)$

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 $e_o = e_i \cdot (\theta_i/\theta_t) \quad \dots(5.30)$

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

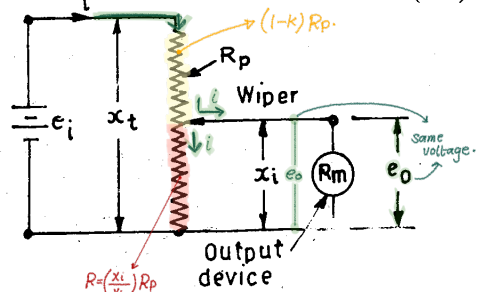


Fig. 5.27. Loaded potentiometer.

① * The equivalent of R & R_m

$$= \frac{R_p \left(\frac{x_i}{x_t}\right) * R_m}{R_p \left(\frac{x_i}{x_t}\right) + R_m} = \frac{R_p k \cdot R_m}{R_p k + R_m}$$

② * The equivalent resistant (total).

$$(1-k)R_p + \frac{R_p k \cdot R_m}{R_p k + R_m} = \frac{(R_p^2 k - R_p^2 k^2 + R_m R_p - R_m R_p k) + R_p R_m k}{R_p k + R_m}$$

$$R = \frac{R_p^2 k (1-k) + R_m R_p}{R_p k + R_m}$$

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 = $(i) * (R)$

$$= \frac{e_i (R_p k + R_m)}{R_p^2 k (1-k) + R_m R_p} \cdot \left(\frac{R_p k \cdot R_m}{R_p k + R_m} \right)$$

$$= \frac{e_i (k)}{\frac{R_p}{R_m} (k(k-1)) + 1}$$

\therefore In the ideal case $\rightarrow R_m = \infty$, no loading effect.
 $\left(\frac{R_p}{R_m} (k(k-1))\right) = \text{zero}$
 $e_o = e_i (k)$
 $= e_i \left(\frac{x_i}{x_t}\right)$

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.

$$e_0 = (x_i/x_t) e_i = K e_i \quad \dots(5.31)$$

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 :

$$\frac{(x_i/x_t) R_p R_m}{(x_i/x_t) R_p + R_m} = \frac{K R_p R_m}{K R_p + R_m} \quad \dots(5.32)$$

The total resistance seen by the source is :

$$R = R_p (1 - K) + \frac{K R_p R_m}{K R_p + R_m} = \frac{K R_p^2 (1 - K) + R_p R_m}{K R_p + R_m} \quad \dots(5.33)$$

$$\therefore \text{Current } i = \frac{e_i}{R} = \frac{e_i (K R_p + R_m)}{K R_p^2 (1 - K) + R_p R_m}$$

The output voltage under load conditions is :

$$e_0 = i \frac{K R_p R_m}{K R_p + R_m} = \frac{e_i (K R_p + R_m)}{K R_p^2 (1 - K) + R_p R_m} \cdot \frac{K R_p R_m}{(K R_p + R_m)}$$

$$= \frac{e_i K}{K (1 - K) (R_p/R_m) + 1} \quad \dots(5.34)$$

The ratio of output voltage to input voltage under load conditions is :

$$\frac{e_0}{e_i} = \frac{K}{K (1 - K) (R_p/R_m) + 1} \quad \dots(5.35)$$

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 $R_m = \infty$, $e_0/e_i = K$.

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.

Error = output voltage under load - output voltage under no load

$$= \frac{e_i K}{[K (1 - K) (R_p/R_m) + 1]} - e_i K = - e_i K \left[\frac{K^2 (1 - K)}{K(1 - K) + R_m/R_p} \right] \quad \dots(5.36)$$

Based upon full-scale output, this relationship may be written as :

$$\% \epsilon = - \left[\frac{K^2 (1 - K)}{K (1 - K) + (R_m/R_p)} \right] \times 100 \quad \dots(5.37)$$

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 measurement
= $10 \times 1/200 = 0.05$ mm.

Example 5.5. A variable potential divider has a total resistance of $2 \text{ k}\Omega$ and is fed from a 10 V d.c. supply. The output is connected to a load resistance of $5 \text{ k}\Omega$. 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 .

$R_p = 2000 \Omega$
 $R_m = 5000 \Omega$

Solution. We have $R_p = 2 \text{ k}\Omega$ and $R_m = 5 \text{ k}\Omega$
 From Eqn. 5.36, error is,

$$-e_i \left[\frac{K^2 (1 - K)}{K (1 - K) + R_m/R_p} \right]$$

عادي نستخدم المعادلة الى اشتقها
 وما نرجع نكتبها مع السؤال.

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)

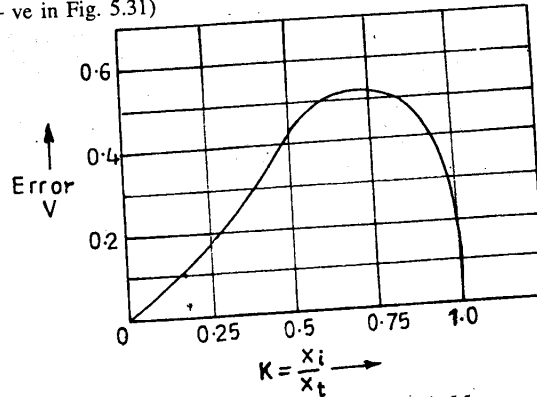


Fig. 5.31. Graph of results of Example 5.5.

Example 5.6. A resistive potential divider $R_1 R_2$ with a resistance of 5000Ω and a shaft stroke of 125 mm is used in the arrangement shown in Fig. 5.32. Potentiometer $R_3 R_4$ has a resistance of 5000Ω and $e_i = 5.0 \text{ V}$. 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 $R_3 R_4$ 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 .

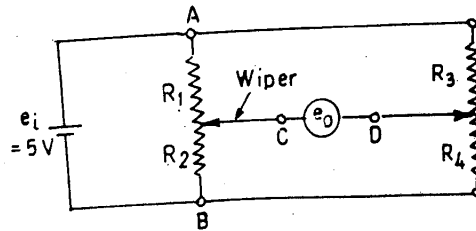


Fig. 5.32. Diagram of Exmple 5.6.

Solution. Total length of $AB = 125 \text{ mm}$ Midpoint of $AB = 62.5 \text{ mm}$ from either A or B. If the wiper moves 12.5 mm inward towards A from midstroke, its distance from B becomes $62.5 + 12.5 = 75 \text{ mm}$.

* 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 | Force to displacement. Pressure to displacement. Pressure to displacement. Force to displacement. |
| 1. Proving ring 2. Bourdon tube 3. Bellows 4. Diaphragm 5. Spring | |
| C. Mass | Forcing function to displacement. Force to displacement. Pressure to displacement. |
| 1. Seismic mass 2. Pendulum scale 3. Manometer | |
| D Thermal | Temperature to electric current. Temperature to displacement. Temperature to phase. |
| 1. Thermocouple → voltage 2. Bimaterial → Resistance 3. Temp-stick | |
| E Hydropneumatic | Fluid level to displacement. Specific gravity to displacement. |
| 1. Static | |
| (a) Float (b) Hydrometer | |
| 2. Dynamic | Velocity to pressure. Velocity to pressure. Velocity to pressure. Velocity to force. Linear to angular velocity. |
| (a) Orifice (b) Venturi (c) Pitot tube (d) Vanes (e) Turbines | |

using electrical
signal to measure
the temp.

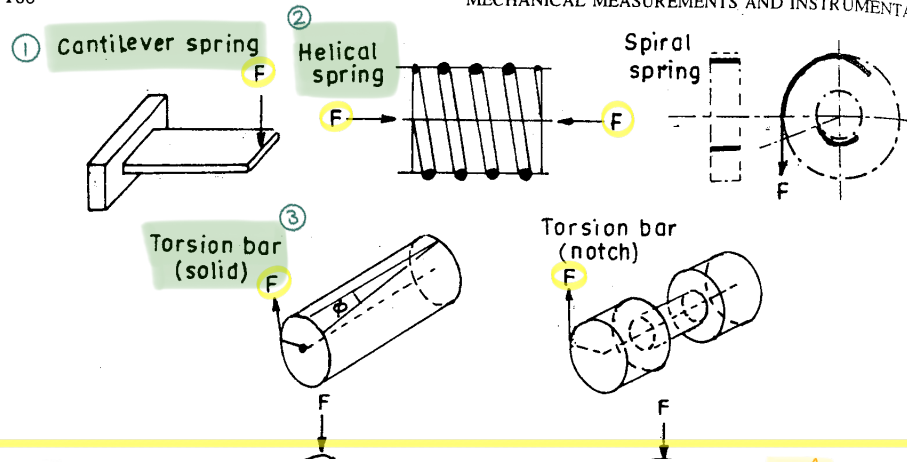
These mechanical quantities include force, pressure, displacement, flow rate, temperature and the list is perhaps unending.

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 \rightarrow higher displacement at the endpoint.

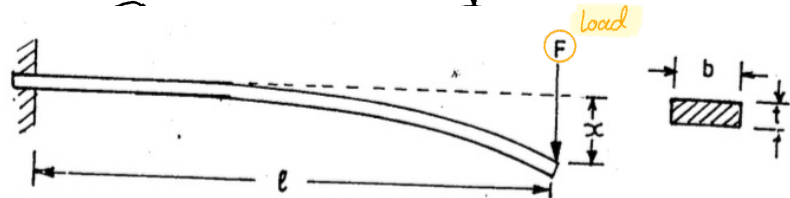


Fig. 5.2. Cantilever.

Deflection at the free end where

F = applied force ; N , l = length of cantilever ; m , E = modulus of elasticity ; N/m^2 , I = moment of inertia = $(\frac{1}{12}) bt^3 ; m^4$, b = width of cantilever ; m , t = thickness of cantilever ; m . $K = F/x = 3 EI/l^3 N/m$

$$x = \frac{F l^3}{3 EI} \quad \dots(5.1)$$

Stiffness of cantilever

$$K = F/x = 3 EI/l^3 N/m \quad \dots(5.2)$$

* 5.3.2. Helical Spring. Fig. 5.3 shows a close coiled helical spring subjected to a compressive force F .

Displacement of spring :

$$x = \frac{8 F D^3 n}{G d^4} \quad \dots(5.3)$$

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/m^2 .

$$\text{Stiffness of spring } K = \frac{F}{x} = \frac{G d^4}{8 D^3 n} N/m. \quad \dots(5.4)$$

$$\text{Maximum shear stress, } \tau = \frac{8 F D}{\pi d^3} N/m^2. \quad \dots(5.5)$$

* 5.3.3. Spiral Spring. Fig. 5.4 shows a flat spiral spring subjected to a torque T .

The deflection of the spring is :

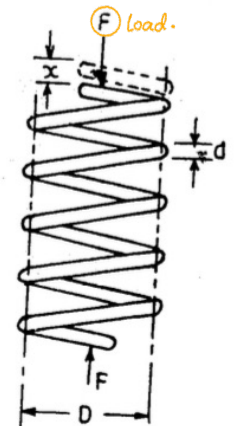


Fig. 5.3. Closed coiled helical spring.

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.

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*

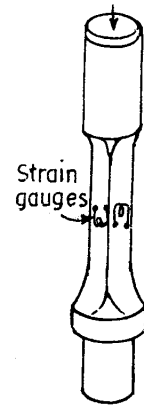


Fig. 5.6. Load cells.

Pressure for Fluid.

Higher amount of Displacement located at the center.

higher area of contact with the Fluid.
more sensitive for change.

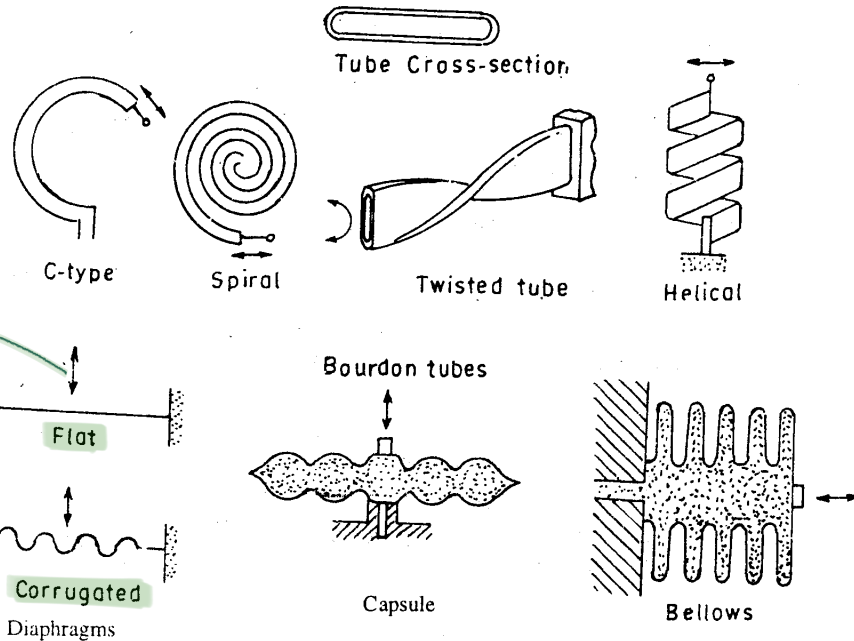


Fig. 5.7. Pressure sensitive primary devices.

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.

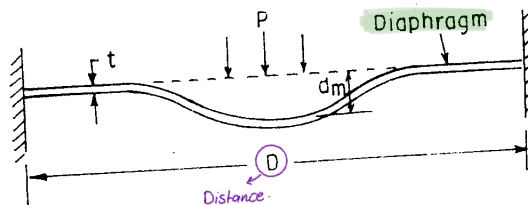


Fig. 5.8. Flat diaphragm.

The pressure is given by :

device to measure
the pressure.

$$P = \frac{256 Et^3 d_m}{3(1 - \nu^2) D^4} \text{ N/m}^2$$

t : thickness of wire

d_m : max. displacement

E : modulus of elasticity

ν : poisson ratio.

(5.12)