**Module-1**

**Basic Principles of Engineering Metrology:**

The importance of metrology as a scientific discipline gained momentum during the industrial revolution. Continuing technological advancement further necessitated refinement in this segment. Metrology is practised almost every day, often nknowingly, in our day-to-day tasks. Measurement is closely associated with all the activities pertaining to scientific, industrial, commercial, and human aspects. Its role is ever increasing and encompasses different fields such as communications, energy, medical sciences, food sciences, environment, trade, transportation, and military applications. Metrology concerns itself with the study of measurements. It is of utmost importance to measure different types of parameters or physical variables and uantify each of them with a specific unit. Thus, measurement is an act of assigning an accurate and precise value to a physical variable.

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

We know that accuracy of measurement is very important for manufacturing a quality product. Accuracy is the degree of agreement of the measured dimension with its true magnitude. It can also be defined as the maximum amount by which the result differs from the true value or as the nearness of the measured value to its true value, often expressed as a percentage. True value may be defined as the mean of the infinite number of measured values when the average deviation due to the various contributing factors tends to zero. In practice, realization of the true value is not possible due to uncertainties of the measuring process and hence cannot be determined experimentally. Positive and negative deviations from the true value are not equal and will not cancel each other. One would never know whether the quantity being measured is the true value of the quantity or not. Precision is the degree of repetitiveness of the measuring process. It is the degree of agreement of the repeated measurements of a quantity made by using the same method, under similar conditions. In other words, precision is the repeatability of the measuring process. The ability of the measuring instrument to repeat the same results during the act of measurements for the same quantity is known as repeatability. Repeatability is random in nature and, by itself, does not assure accuracy, though it is a desirable characteristic. Precision refers to the consistent reproducibility of a measurement. Reproducibility is normally specified in terms of a scale reading over a given period of time. If an instrument is not precise, it would give different results for the same dimension for repeated readings. In most measurements, precision assumes more significance than accuracy. It is important to note that the scale used for the measurement must be appropriate and conform to an internationally accepted standard. It is essential to know the difference between precision and accuracy. Accuracy gives information regarding how far the measured value is with respect to the true value, whereas precision indicates quality of measurement, without giving any assurance that the measurement is correct. These concepts are directly related to random and systematic measurement errors. Figure 1.1 also clearly depicts the difference between precision and accuracy, wherein several measurements are made on a component using different types of instruments and the results plotted.



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

E = Vm − Vt

where E is the error, Vm the measured value, and Vt the true value.

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



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

**OBJECTIVES OF METROLOGY AND MEASUREMENTS**

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

2. To ensure uniformity of measurements

3. To carry out process capability studies to achieve better component tolerances

4. To assess the adequacy of measuring instrument capabilities to carry out their respective measurements

5. To ensure cost-effective inspection and optimal use of available facilities

6. To adopt quality control techniques to minimize scrap rate and rework

7. To establish inspection procedures from the design stage itself, so that the measuring methods are standardized

8. To calibrate measuring instruments regularly in order to maintain accuracy in measurement

9. To resolve the measurement problems that might arise in the shop floor

10. To design gauges and special fixtures required to carry out inspection

11. To investigate and eliminate different sources of measuring errors

**GENERAL MEASUREMENT CONCEPTS**

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

1. Measurand, a physical quantity such as length, weight, and angle to be measured

2. Comparator, to compare the measurand (physical quantity) with a known standard (reference) for evaluation

3. Reference, the physical quantity or property to which quantitative comparisons are to be made, which is internationally accepted

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

**ERRORS IN MEASUREMENTS**

While performing physical measurements, it is important to note that the measurements obtained are not completely accurate, as they are associated with uncertainty. Thus, in order to analyse the measurement data, we need to understand the nature of errors associated with the measurements. Therefore, it is imperative to investigate the causes or sources of these errors in measurement systems and find out ways for their subsequent elimination. Two broad categories of errors in measurement have been identified: systematic and random errors.

1.7.1 Systematic or Controllable Errors

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

1. Calibration errors

2. Ambient conditions

3. Deformation of workpiece

4. Avoidable errors

Calibration Errors A small amount of variation from the nominal value will be present in the actual length standards, as in slip gauges and engraved scales. Inertia of the instrument and its hysteresis effects do not allow the instrument to translate with true fidelity. Hysteresis is defined as the difference between the indications of the measuring instrument when the value of the quantity is measured in both the ascending and descending orders. These variations have positive significance for higher-order accuracy achievement. Calibration curves are used to minimize such variations. Inadequate amplification of the instrument also affects the accuracy. Ambient Conditions: It is essential to maintain the ambient conditions at internationally accepted values of standard temperature (20 ºC) and pressure (760 mmHg) conditions. A small difference of 10 mmHg can cause errors in the measured size of the component. The most significant ambient condition affecting the accuracy of measurement is temperature. An increase in temperature of 1 ºC results in an increase in the length of C25 steel by 0.3 μm, and this is substantial when precision measurement is required. In order to obtain error-free results, a correction factor for temperature has to be provided. Therefore, in case of measurements using strain gauges, temperature compensation is provided to obtain accurate results. Relative humidity, thermal gradients, vibrations, and CO2 content of the air affect the refractive index of the atmosphere. Thermal expansion occurs due to heat radiation from different sources such as lights, sunlight, and body temperature of operators.

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

**Avoidable Errors**

These include the following:

Datum errors Datum error is the difference between the true value of the quantity being measured and the indicated value, with due regard to the sign of each. When the instrument is used under specified conditions and a physical quantity is presented to it for the purpose of verifying the setting, the indication error is referred to as the datum error. Reading errors These errors occur due to the mistakes committed by the observer while noting down the values of the quantity being measured. Digital readout devices, which are increasingly being used for display purposes, eliminate or minimize most of the reading errors usually made by the observer.

Errors due to parallax effect Parallax errors occur when the sight is not perpendicular to the instrument scale or the observer reads the instrument from an angle. Instruments having a scale and a pointer are normally associated with this type of error. The presence of a mirror behind the pointer or indicator virtually eliminates the occurrence of this type of error. Effect of misalignment These occur due to the inherent inaccuracies present in the measuring instruments. These errors may also be due to improper use, handling, or selection of the instrument. Wear on the micrometer anvils or anvil faces not being perpendicular to the axis results in misalignment, leading to inaccurate measurements. If the alignment is not proper, sometimes sine and cosine errors also contribute to the inaccuracies of the measurement. Zero errors When no measurement is being carried out, the reading on the scale of the instrument should be zero. A zero error is defined as that value when the initial value of a physical quantity indicated by the measuring instrument is a non-zero value when it should have actually been zero. For example, a voltmeter might read 1 V even when it is not under any electromagnetic influence. This voltmeter indicates 1 V more than the true value for all subsequent measurements made. This error is constant for all the values measured using the same instrument. A constant error affects all measurements in a measuring process by the same amount or by an amount proportional to the magnitude of the quantity being measured. For example, in a planimeter, which is used to measure irregular areas, a constant error might occur because of an error in the scale used in the construction of standard or, sometimes, when an incorrect conversion factor is used in conversion between the units embodied by the scale and

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

**Random Errors**

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

value. If n measurements are made using an instrument, denoted by v1, v2, v3, …, vn, then arithmetic mean is given as

 

**Module-2**

**Linear Measurement**

**DESIGN OF LINEAR MEASUREMENT INSTRUMENTS**

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

1. The measuring accuracy of line-graduated instruments depends on the original accuracy of the line graduations. Excessive thickness or poor definition of graduated lines affects the accuracy of readings captured from the instrument.

2. Any instrument incorporating a scale is a suspect unless it provides compensation against wear.

3. Attachments can enhance the versatility of instruments. However, every attachment used along with an instrument, unless properly deployed, may contribute to accumulated error. Wear and tear of attachments can also contribute to errors. Use attachments when their presence improves reliability more than their added chance for errors decreasing it.

4. Instruments such as callipers depend on the feel of the user for their precision. Good quality of the instrument promotes reliability, but it is ultimately the skill of the user that ensures accuracy. Therefore, it is needless to say that proper training should be imparted to the user to ensure accurate measurements.

5. The principle of alignment states that the line of measurement and the line of dimension being measured should be coincident. This principle is fundamental to good design and ensures accuracy and reliability of measurements.

6. Dial versions of instruments add convenience to reading. Electronic versions provide digital readouts that are even easier to read. However, neither of these guarantees accuracy and reliability of measurements unless basic principles are adhered to.

7. One important element of reliability of an instrument is its readability. For instance, the smallest division on a micrometer is several times larger than that on a steel rule of say 0.1 mm resolution, which is difficult to read. However, the micrometer provides better least count, say up to 0.01 mm, compared to the same steel rule. Therefore, all other things being equal, a micrometer is more reliable than even a Vernier scale. However, micrometers have a lesser range than Vernier.

8. If cost is not an issue, digital instruments may be preferred. The chief advantage of the electronic method is the ease of signal processing. Readings may be directly expressed in the required form without additional arithmetic. For example, they may be expressed in either metric or British units, and can also be stored on a memory device for further use and analysis.

9. Whenever a contact between the instrument and the surface of the job being measured is inevitable, the contact force should be optimum to avoid distortion. The designer cannot leave the fate of the instrument on the skill of the user alone. A proper device like a ratchet stop can limit the contact force applied on the job during measurements, thereby avoiding stress on the instrument as well as distortion of the job.

**SCALED INSTRUMENTS**

Rules are useful for many shop floor measurements. However, measurements of certain components require some mechanical means to either hold the measuring device steadily against the component being measured or capture the reading, which can be read at leisure. Another important advantage of a scaled instrument is that the least count of measurement can be improved greatly compared to an ordinary steel rule. Most of the modern scaled instruments provide digital display, which comes with a high degree of magnification. Measurements can be made up to micron accuracy. This section presents three scaled instruments, namely depth gauge, combination set, and callipers, which are necessary accessories in a modern metrology laboratory. 4.6.1 Depth Gauge Depth gauge is the preferred instrument for measuring holes, grooves, and recesses. It basically consists of a graduated rod or rule, which can slide in a T-head (simply called the head) or stock. The rod or rule can be locked into position by operating a screw clamp, which facilitates accurate reading of the scale. Figure 4.12 illustrates a depth gauge, which has a graduated rule to read the measurement directly. The head is used to span the shoulder of a recess, thereby providing the reference point for measurement. The rod or rule is pushed into the recess until it bottoms. The screw clamp helps in locking the rod or rule in the head. The depth gauge is then withdrawn, and reading is recorded in a more convenient position. Thus, depth gauge is useful for measuring inaccessible points in a simple and convenient manner. As already pointed out, either rods or rules can be used in depth gauges for the purpose of measurement. Although a slender rod can easily transfer measurements from narrow and inaccessible holes and recesses, the instrument cannot directly display the reading. One has to use another rule to measure the length of the protruded rod and record the measurement. This may lead to errors in measurements and reduce the reliability of the instrument. To overcome this problem, a graduated rod can be used, which can indicate the measurement directly. However, it is somewhat difficult to read graduations from a slender rod. Therefore, a narrow flat scale is the preferred choice for depth gauges. The rule is often referred to as the blade and is usually 150 mm long. The blade can accurately read up to 1 or ½ mm. As already pointed out, the head is used to span the shoulder of a recess, thereby providing the reference point for measurement. This is illustrated in the rod-type depth gauge shown in Fig. 4.13. The end of the rod butts against the end surface to provide the measured point. Whenever depth needs to be measured, the projected length of the rod from the head is made very less. The lower surface of the head is firmly held against the job to ensure accurate location of the measured point. Now the rod is lowered until it butts against the surface of the job, thereby marking the measured point. The screw clamp is tightened, the instrument is slowly taken out, and the depth of the hole is read in a convenient position. This method is preferred for narrow recesses and holes. To summarize, the depth gauge is first positioned against the reference point, followed by the capture of the measured point in order to complete the measurement process.

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

1. The job size is limited by the width of the head of the depth gauge. Usually, the maximum width of the hole that can be spanned is about 50 mm.

2. The base of the head should be perpendicular to the line of measurement. Otherwise, the line of measurement will be skewed, resulting in erroneous readings.

3. The end of the blade must butt against the desired reference. This will be rather difficult to achieve, especially in blind holes.

4. The end of the blade and the lower surface of the head are always in contact with the job being measured. Therefore, these surfaces will undergo wear and tear. The instrument should be periodically checked for accuracy and replaced if the wear amounts to one graduation line of the instrument.

**VERNIER INSTRUMENTS**

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

The vernier scale was invented in its modern form in 1631 by the French mathematician Pierre Vernier (1580–1637). Vernier instruments are being used for more than two centuries. The American, Joseph Brown, is credited with the invention of the vernier calliper. As is perhaps known to a student, a vernier scale provides a least count of up to 0.01 mm or less, which remarkably improves the measurement accuracy of an instrument. It has become quite common in the modern industry to specify dimensional accuracy up to 1 μm or less. It is the responsibility of an engineer to design and develop measuring instruments that can accurately measure up to such levels. It will not be out of place here to briefly brush up our memory of the basic principles of a vernier scale. A vernier scale comprises two scales: the main scale and the vernier scale. Consider the scale shown in Fig. 4.23. Let us say that the main scale has graduations in millimetres up to a minimum division of 1 mm. The vernier scale also has graduations, having 10 equal divisions. In this example, 10 vernier scale divisions (VSDs) equal nine main scale divisions (MSDs). Obviously, the value of one VSD is less than one MSD. Such a vernier scale is called a forward vernier. On the other hand, suppose 10 VSDs equal 11 MSDs, the value of one VSD is more than that of one MSD. Such a vernier scale is called the backward vernier. Calculation of least count The minimum length or thickness that can be measured with a vernier scale is called the least count. For a forward vernier shown in Fig. 4.23,

N VSD = (N−1) MSD

1 VSD = (N−1)/N MSD

Least count = 1 MSD − 1 VSD

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

Least count = [1− (N − 1)/N] MSD

Least count = 1 MSD/N

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



**Vernier Calliper**

A vernier calliper consists of two main parts: the main scale engraved on a solid L-shaped frame and the vernier scale that can slide along the main scale. The sliding nature of the vernier has given it another name—sliding calliper. The main scale is graduated in millimetres, up to a least count of 1 mm. The vernier also has engraved graduations, which is either a forward vernier or a backward vernier. The vernier calliper is made of either stainless steel or tool steel, depending on the nature and severity of application. Figure 4.25 illustrates the main parts of a vernier calliper. The L-shaped main frame also serves as the fixed jaw at its end. The movable jaw, which also has a vernier scale plate, can slide over the entire length of the main scale, which is engraved on the main frame or the beam. A clamping screw enables clamping of the movable jaw in a particular position after the jaws have been set accurately over the job being measured. This arrests further motion of the movable jaw, so that the operator can note down the reading in a convenient position. In order to capture a dimension, the operator has to open out the two jaws, hold the instrument over the job, and slide the movable jaw inwards, until the two jaws are in firm contact with the

job. A fine adjustment screw enables the operator to accurately enclose the portion of the job where measurement is required by applying optimum clamping pressure. In the absence of the fine adjustment screw, the operator has to rely on his careful judgement to apply the minimum force that is required to close the two jaws firmly over the job. This is easier said than done, since any excessive application of pressure increases wear and tear of the instrument and may also cause damage to delicate or fragile jobs. The two jaws are shaped in such a manner that they can be used to measure both inside and outside dimensions. Notice the nibs in Fig. 4.25, which can be used to measure inside dimension. Figure 4.26 illustrates the method of measuring inside and outside dimensions using a vernier calliper. Whenever the vernier slides over the main frame, a depth-measuring blade also slides in and out of the beam of the calliper. This is a useful attachment for measuring depths to a high degree of accuracy. Divider setting holes are provided, which enable the use of a divider to aid the measurement process. Measuring a diameter is easier than measuring between flat surfaces, because the diameter is the greatest distance separating the reference and the measured points. Compared to the measurement between flat surfaces, the area of contact between the calliper and the job is much lesser in diameter measurement. Therefore, the resultant force acting either on the job or on the jaws of the calliper is lesser, with the result that there is no deformation or buckling of the jaws. This not only improves the accuracy of measurement, but also reduces the wear and tear of the instrument. Whether the measurement is done for the inside diameter or outside diameter, the operator has to rely on his/her feel to judge if proper contact is made between the measured surfaces and also that excessive force is not exerted on the instrument or the job. Continued closing of the calliper will increase the springing. High gauging pressure causes rapid wear of the jaws, burnishes the part (localized hardening of metal), and may cause damage to the calliper.

The following guidelines are useful for the proper use of a vernier calliper:

1. Clean the vernier calliper and the job being measured thoroughly. Ensure that there are no burrs attached to the job, which could have resulted from a previous machining operation.

2. When a calliper’s jaws are fully closed, it should indicate zero. If it does not, it must be recalibrated or repaired.

3. Loosen the clamping screw and slide the movable jaw until the opening between the jaws is slightly more than the feature to be measured.

4. Place the fixed jaw in contact with the reference point of the feature being measured and align the beam of the calliper approximately with the line of measurement.

5. Slide the movable jaw closer to the feature and operate the fine adjustment screw to establish a light contact between the jaws and the job.

6. Tighten the clamp screw on the movable jaw without disturbing the light contact between the calliper and the job.

7. Remove the calliper and note down the reading in a comfortable position, holding the graduations on the scale perpendicular to the line of sight.

8. Repeat the measurement a couple of times to ensure an accurate measurement.

9. After completing the reading, loosen the clamping screw, open out the jaws, and clean and lubricate them.

10. Always store the calliper in the instrument box provided by the supplier. Avoid keeping the vernier calliper in the open for long durations, since it may get damaged by other objects or contaminants.

11. Strictly adhere to the schedule of periodic calibration of the vernier calliper.

**Dial Calliper**

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**Vernier Depth Gauge & Vernier Height Gauge**

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**MICROMETER INSTRUMENTS:**

The word ‘micrometer’ is known by two different meanings. The first is as a unit of measure, being one thousandth of a millimetre. The second meaning is a hand-held measuring instrument using a screw-based mechanism. The word micrometer is believed to have originated in Greece, the Greek meaning for this word being small. The first ever micrometer screw was invented by William Gascoigne of Yorkshire, England, in the 17th century and was used in telescopes to measure angular distances between stars. The commercial version of the micrometer was released by the Browne & Sharpe Company in the year 1867. Obviously, micrometer as an instrument has a long and cherished history in metrological applications. There have been many variants of the instrument, and modern industry makes use of highly sophisticated micrometers, such as digital micrometers and laser scan micrometers. A micrometer can provide better least counts and accuracy than a vernier calliper. Better accuracy results because of the fact that the line of measurement is in line with the axis of the instrument, unlike the vernier calliper that does not conform to this condition. This fact is best explained by Abbe’s principle, which states that ‘maximum accuracy may be obtained only when the standard is in line with the axis of the part being measured’. Figure 4.31 illustrates the relevance of Abbe’s law for micrometers and vernier callipers.



**Outside Micrometer:**

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**Digital Micrometer:**

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**Inside Micrometer Calliper : & Depth Micrometer**

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