1
Introduction

1.1. What is Metrology

The word metrology has a long tradition and is derived from the Greek word for measure. It is well-known saying that the knowledge about anything is complete only when it can be expressed in numbers and something is known about it. Thus for every kind of quantity measured, there must be a unit to measure it and express it in numbers of that unit. Further, in order that this unit is followed by all and not one who is taking the measurements, there must be a universal standard and the various units for various parameters of importance must be standardised. Most important parameter in metrology is the 'length' which can be measured in several forms and in several ways.

Measurements play a vital role in every field of investigation and present day scientific and technological progress has resulted from progress in the field of measurements. In general, measurements are made to increase our knowledge and understanding of the world with a view to lead a better life. Measurement science is vital for trade and commerce and is the basis of modern science and technology.

In metrology, which literally is the science of measurements we have to go one step ahead and bother ourselves about the correctness of measurement also. We have to see whether the result is given with the sufficient correctness and accuracy for the particular need or not. Thus we are primarily concerned with methods of measurement based on agreed units and standards. Metrology is thus concerned with the establishment, reproduction, conservation and transfer of units of measurements and their standards. The practice of metrology involves precise measurements requiring the use of apparatus and equipments (instruments and necessary adjuncts) to permit the degree of accuracy required to be obtained.

Metrology, the science of measurements, includes all aspects both theoretical and practical with reference to measurements, whatever their uncertainty, and in whatever fields of science or technology they occur. Thus metrology is also the science of measurement associated with the evaluation of its uncertainty. It is important to understand that only to measure is not the specifity of metrology but the core of metrology lies in the validation of the result, particularly by specifying its actual limitations. Metrology is not restricted only to standards of length and mass but other parameters in sectors of social concern, such as health, safety, and environment protection also. Making mastery of the science of measurement is a prerequisite for progress in science itself. Industrial manufacturing and many fields of life call for activity at a high scientific and technical level at which any progress achieved has to be accomplished by progress in metrology. The increasing automation of manufacture requires the highest level of accuracy. One must remember the famous saying that man's knowledge of nature, the universe, and how to adapt nature to his purpose, advances in step with his ability to measure precisely.

The metrologist has to understand the underlying principles to be able to design and develop new instruments and also to use the available instruments in the best way. Metrology is therefore also concerned with the methods, execution and estimation of accuracy of measurements ; the measuring instruments and the inspectors. Today's standard of precision and reliability are so high that man's basic instincts and senses are inadequate to cope with them. To this end, use has to be made of precision measuring instruments and various types of conventional and sophisticated gauges and comparators.

Thus, it can be said that metrology is mainly concerned with (*i*) establishing the units of measurements, reproducing these units in the form of standards, and ensuring the uniformity of measurements, (*ii*) developing methods of measurement, (*iii*) analysing the accuracy of methods of measurement, establishing uncertainty of measurement, researching into the causes of measuring errors, and eliminating these.

In the broader sense, metrology is not limited to length measurement but is also concerned with the industrial inspection and its various techniques. Due to big industrial revolution and great advancement, industrial inspection does not simply mean the fulfilling of the specifications laid down by the manufacturers. Rather inspection in real sense is concerned with the checking of a product at various stages in its manufacture right from the raw material form to the finished products and even assembled parts in the form of machine also. Inspection is carried out with gauges and the metrologist is intimately concerned with the design, manufacturing and testing of gauges of all kinds. Dynamic metrology is concerned with measuring small variations of continuous nature. The measurement science today has developed to electronically operated and controlled equipments, computer-aided systems for on-line monitoring, opto-mechanical, laser and fibre optics based instruments, etc.

As regards length measurement (dimensional inspection), we will be dealing with non-precision and precision linear measurements and study the various instruments used for this purpose. The standardisation of various units is also important and we will study what are the various standards for linear measurements and how attempts are made to preserve and maintain these standards. We will also see how the light wave standard helps us in doing away with material standards. For very precise measurements, methods based on light wave interference phenomena will also form a separate chapter.

Metrological activities start from establishment of measurement standards, appraisal of various physical parameters including dimensions, development of measuring instruments and techniques, and calibration of test and measurement equipments. All this is essential for correct operative measurement for quality and products and services delivered by the industry. Present day industry demands not only one time achievability, but aims for conformity involving such aspects as repeatability, reproducibility, interchangeability, of very many dimensions and characteristics and evidence thereof, for confidence of both producers and customers. This is possible by creation of standards and measurement techniques.

Due to mass production, it can be very easily realised that it is not possible to measure the various elements of a component by conventional methods. Thus other devices, *i.e.* gauges and comparators will be studied in detail. Further it is also not advisable to measure all the components in mass production if they are coming out of automatic machines. It will be seen that inspection of a few components out of a big lot is sufficient under the study of statistical quality control, the knowledge of which is very essential now-a-days.

As regards assembly and fitting of various components, some system of limits and fits has to be followed throughout and we will study the Indian Standard for 'Limits and Fits'. For assembled products in form of machine, it is essential that the relative movements of various parts of machine take place in a desired way. For this purpose study of machine tool alignment tests is very essential.

Many times in actual production, angle measurement presents a big problem and its thorough understanding and various techniques involved in it and circular division form an important part of metrology. Sometimes we come across various measurements which are really quite typical and problems of this type can be easily solved with the help of some trigonometrical relations. Such measurements will be studied in the chapter of Miscellaneous Measurements.

It may be emphasised here that man has to handle various instruments and sense of 'feel' plays very important role. In order that all people get same readings for a component by the same instrument, the instrument should be designed in such a way that always constant pressure is applied between the component and the instrument. Also instrument must be held such that the sense of 'feel' present in hand is free to give correct decision. However, in Universal Machines, an attempt is made to eliminate human errors due to different senses of touch and feel.

Good machines and their proper functioning calls for very good finished surfaces and thus study of the surface finish and various methods to estimate it quantitatively is very essential. A most commonly used tool in the hand of metrologist is 'dial-indicator' which will be studied in detail separately. Testing of gauges and dynamic measurements also deserve full attention.

We will also be dealing with the screw thread measurement and gear measurement and gauges for screw threads, as these are most popular parts one comes across in a workshop and machines.

A chapter is also devoted to non-destructive testing of metals and alloys to make one familiar with those methods which do not destroy the material and at the same time check all the desired properties and examine the internal structure of materials for homogeneity.

There is a great awareness about quality and industries are adopting the approach of Total Quality Management. Chapters have thus been devoted to Quality Assurance Programmes and Total Quality Management with reference to ISO 9000. A chapter is also devoted to Machine Vision Systems.

In broader sense, metrology (the science and art of precision measurement, testing and evaluation) is the mother science for technological development. The advancements in industry depend, to a great extent, on the quality and reliability of dimensional accuracy and precision measurement of other physical characteristics.

1.1.1. Legal Metrology. Legal Metrology is that part of metrology which treats units of measurement, methods of measurement and the measuring instruments, in relation to the statutory, technical and legal requirements. It assures security and appropriate accuracy of measurements. Lack of legislation regarding various measures will lead to great uncertainty.

Legal metrology is directed by a national organisation, *viz.* National Service of Legal Metrology whose object is to resolve problems of legal metrology in a particular country. Its functions are to ensure the conservation of national standards and to guarantee their accuracy by comparison with international standards ; and also to impart proper accuracy to the secondary standards of the country by comparison with international standards.

The contemporary organisation of metrology includes a number of international organisations *viz.* (*a*) The International Organisation of Weights and Measures : and (*b*) National Service of Legal Metrology whose ultimate object is to maintain uniformity of measurements throughout the world.

The activities of the service of Legal Metrology are : control (testing, verification, standardisation) of measuring instruments ; testing of prototypes/models of measuring instruments ; examination of a measuring instrument to verify its conformity to the statutory requirements, etc.

Legal metrology has application in :

(*i*) Commercial transactions (net quantity)

(*ii*) Industrial measurements (proper control on accuracy of measurement, so as to ensure interchangeability with a view to promoting mass production.

(*iii*) Measurements needed for ensuring public health and human safety.

A national law relating to legal metrology covers the following points :

(*i*) Legal units of measurements. In 1976, Parliament enacted comprehensive law, the Standards of Weights and Measures Act 1976, to establish the International System of Units (SI), to regulate inter-State trade or commerce in weights and measures, and to provide for other matters important from the view-point of consumer protection.

(*ii*) physical presentation of legal units ;

(*iii*) hierarchy of standards—their maintenance and custody ;

National Standards (Echelon-I)

Reference Standards (Echelon-II)

Secondary Standards (Echelon-III A)

Working Standards (Echelon-III B)

(*iv*) specifications or technical regulations of measuring instruments as regards their metrological and technical requirements ;

(*v*) metrological control on measuring instruments ; (approval of model, initial verification, periodical verification ; verification after repairs, inspection of the use of measuring instruments)

(*vi*) metrological control on pre-packed goods ;

(*vii*) control on manufacture, repair and sale of measuring instruments ;

(*viii*) organisation/service concerned with legal metrology ;

(*ix*) levy and collection of fees ;

(*x*) penalties for contraventions ;

(*xi*) training of personnel.

1.1.2. Deterministic Metrology. This is a new philosophy in which part measurement is replaced by process measurement. In the deterministic metrology, full advantage is taken of the deterministic nature of production machines (machines under automatic control are totally deterministic in performance) and all of the manufacturing sub-systems are optimised to maintain deterministic performance within acceptable quality levels. In this science, the system processes are monitored by temperature, pressure, flow, force, vibration, accoustic "finger printing" sensors, these sensors being fast and non-intrusive. The new technique such as 3D error compensation by CNC (Computer Numerical Control) systems and expert systems are applied, leading to fully adaptive control. This technology is used for very high precision manufacturing machinery and control systems to achieve microtechnology and nanotechnology accuracies.

1.2. Need of Inspection

In order to determine the fitness of anything made, man has always used inspection. But industrial inspection is of recent origin and has scientific approach behind it. It came into being because of mass production which involved interchangeability of parts. In old craft, same craftsman used to be producer as well as assembler. Separate inspections were not required. If any component part did not fit properly at the time of assembly, the craftsman would make the necessary adjustments in either of the mating parts so that each assembly functioned properly. So actually speaking, no two parts will be alike and there was practically no reason why they should be.

Now new production techniques have been developed and parts are being manufactured in large scale due to low-cost methods of mass production. So hand-fit methods cannot serve the purpose any more. When large number of components of same part are being produced, then any part would be required to fit properly into any other mating component part. This required specialisation of men and machines for the performance of certain operations. It has, therefore, been considered necessary to divorce the worker from all round crafts work and to supplant hand-fit methods with interchangeable manufacture.

The modern production techniques require that production of complete article be broken up into various component parts so that the production of each component part becomes an independent process. The various parts to be assembled together in assembly shop come from various shops. Rather some parts are manufactured in other factories also and then assembled at one place. So it is very essential that parts must be so fabricated that the satisfactory mating of any pair chosen at random is possible. In order that this may be possible, the dimensions of the component part must be confined within the prescribed limits which are such as to permit the assembly with a predetermined fit. Thus industrial inspection assumed its importance due to necessity of suitable mating of various components manufactured separately. It may be appreciated that when large quantities of work-pieces are manufactured on the basis of interchangeability, it is not necessary to actually measure the important features and much time could be saved by using gauges which determine whether or not a particular feature is within the prescribed limits. The methods of gauging, therefore, determine the dimensional accuracy of a feature, without reference to its actual size.

The purpose of dimensional control is however not to strive for the exact size as it is impossible to produce all the parts of exactly same size due to so many inherent and random sources of errors in machines and men. The principal aim is to control and restrict the variations within the prescribed limits. Since we are interested in producing the parts such that assembly meets the prescribed work standard, we must not aim at accuracy beyond the set limits which, otherwise is likely to lead to wastage of time and uneconomical results.

Lastly, inspection led to development of precision inspection instruments which caused the transition from crude machines to better designed and precision machines. It had also led to improvements in metallurgy and raw material manufacturing due to demands of high accuracy and precision. Inspection has also introduced a spirit of competition and led to production of quality products in volume by eliminating tooling bottle-necks and better processing techniques.

1.2.1. Measuring Means. The means of measurements could be classified as follows :

(*i*) Standards (Reference masters or setting standards)—These are used to reproduce one or several definite values of a given quantity.

(*ii*) Fixed gauges—These are used to check the dimensions, form, and position of product features.

(*iii*) Measuring instruments—These are used to determine the values of the measured quantity.

1.3. Physical Measurement

Measurement is a complex of operations carried out by means of measuring instruments to determine the numerical value of the size which describes the object of measurement.

A physical measurement could be defined as the act of deriving quantitative information about a *physical object* or action by *comparison* with a *reference*. It will be noted from this definition that there are three important elements of a measurement, *viz*, (*i*) measurand, *i.e.* the physical quantity or property like length, angle etc. being measured, (*ii*) comparison or comparator, *i.e.* the means of comparing measurand with some reference to render a judgement and (*iii*) reference, *i.e.* the physical quantity or property to which quantitative comparisons are made. All these three terms would be very clear from the following example of a direct measurement using a calibrated fixed reference. Say, a mechanic has to measure the length of a surface table (measurand). For this, first he lays his rule (reference) alongside the table ; he then carefully aligns the zero end of his rule with one end of the table ; and finally he compares the length of table (measurand) with the graduation on his rule (reference) by eye (comparator).

Such examples of direct measurement using a calibrated fixed reference are plenty in the field of Metrology. For example, measurements of length using vernier calliper, micrometer screw gauge, measurement of angle using bevel protractor etc. Many measurements are made using inferential methods, *e.g.* measurement of pitch diameter or threads using three wire method. Such measurements are also frequently encountered when it is not possible to measure a measurand directly. Such methods are dependent on direct relationship (mathematical or otherwise) between the measurand and the actual measurement being made.

In modern measuring instruments which employ electrical principles, the measured parameter is sensed and converted into electrical quantity such as voltage (there being a direct relationship between the two), which is measured by a null measurement using a calibrated variable reference. The variable reference (by potentiometric voltmeter) is adjusted until an indicator shows that no voltage differential exists between the reference and the unknown voltage. Under such a condition of null, the reference voltage must be equal to the unknown voltage. The purpose of making measurement could be either to quantify the measurand (information), or, provide a historical profile to be referred to at other times (record) or use the information to produce action such as to produce correct size on machine tool (control). The measurement system to be employed will depend on the objective of the measurement to be fulfilled. A modern measurement system utilising electrical techniques responds to the measurand, effects a comparison with the reference and provides information based on that comparison.

However, the direct measurement system using a calibrated fixed reference is more conventional in the field of Metrology. Of course there are several other methods of measurements which are also used in this field.

Principle of measurement. It is the physical phenomenon utilised in the measurement.

Method of measurement. It is the way the measuring principles and measuring means are used.

Nominal size (Basic Size). It is the size on which the limits of size are based and which is assigned to a part in accordance with its function.

True size. It is the theoretical size of a dimension, which is free from any errors of measurement.

Actual Size. It is the value of size obtained through measurement with the permissible measuring error.

Exact size. It is the value of size obtained with the highest metrological accuracy attainable in practice.

Approximate Size. It is the value of size obtained with an error exceeding the permissible error of measurement and requiring refinement.

Error of measurement. It is the difference between the true value of the size being measured and the value found by measurement. Error pertains to a measurement and not to an instrument.

Correction. It is the amount which should be algebraically added to the indicated value to obtain the actual value of the size being measured. The correction is numerically equal to the error, but opposite in sign.

Correctness of measurement. It is quantitative characteristic showing how close to zero are the systematic errors of measurement results.

Reliability of measurement. It is a qualitative characteristic which implies confidence in the measured results depending on whether or not the frequency distribution characteristics of their deviations from the true values of the corresponding quantities are known.

Verification. It is the process of testing an instrument for the purpose of assessing the indication errors and determining whether setting standards or measuring instruments meet the prescribed specifications.

Calibration. It is the process of determining the values of the quantity being measured corresponding to a pre-established arbitrary scale.

1.4. Measuring Instruments

Measuring Instruments are measuring devices that transform the measured quantity or a related quantity into an indication or information.

Measuring instruments can either indicate directly the value of the measured quantity or only indicate its equality to a known measure of the same quantity (*e.g.* equal arm balance, or null detecting galvanometer). They may also indicate the value of the small difference between the measured quantity and the measure having a value very near to it (comparator).

Measuring instruments usually utilise a measuring sequence in which the measured quantity is transformed into a quantity perceptible to the observer (length, angle, sound, luminous contrast).

Measuring instruments may be used in conjunction with separate material measures (*e.g.* balances using standard masses to compare unknown mass), or they may contain internal parts to reproduce the unit (like graduated rules, a precision thread, etc.)

1.4.1. Measuring range. It is the range of values of the measured quantity for which the error obtained from a single measurement under normal conditions of use does not exceed the maximum permissible error.

The measuring range is limited by the maximum capacity and the minimum capacity.

Maximum capacity is the upper limit of the measuring range and is dictated by the design considerations or by safety requirements or both.

Minimum capacity is the lower limit of the measuring range. It is usually dictated by accuracy requirements. For small values of the measured quantity in the vicinity of zero, the relative error can be considerable even if the absolute error is small.

The measuring range may or may not coincide with the range of scale indication.

1.4.2. Sensitivity. It is the quotient of the increase in observed variable (indicated by pointer and scale) and the corresponding increase in the measured quantity.

It is also equal to the length of any scale division divided by the value of that division expressed in terms of the measured quantity.

The sensitivity may be constant or variable along the scale. In the first case, we get linear transmission and in the second case, we get a non-linear transmission.

1.4.3. Scale Interval. It is the difference between two successive scale marks in units of the measured quantity. (In the case of numerical indication, it is the difference between two consecutive numbers).

The scale interval is an important parameter that determines the ability of the instrument to give accurate indication of the value of the measured quantity.

The scale spacing, or the length of scale interval, should be convenient, for estimation of fractions.

1.4.4. Discrimination. It is the ability of the measuring instrument to react to small changes of the measured quantity.

1.4.5. Hysteresis. It is the difference between the indications of a measuring instrument when the same value of the measured quantity is reached by increasing or by decreasing that quantity.

The phenomenon of hysteresis is due to the presence of dry friction as well as to the properties of elastic elements. It results in the loading and unloading curves of the instrument being separated by a difference called the hysteresis error. It also results in the pointer not returning completely to zero when the load is removed.

Hysteresis is particularly noted in instruments having elastic elements. The phenomenon of hysteresis in materials is due mainly to the presence of internal stresses. It can be reduced considerably by proper heat treatment.

1.4.6. Response time. It is the time which elapses after a sudden change in the measured quantity until the instrument gives an indication differing from the true value by an amount less than a given permissible error.

The curve showing the change of indication of an instrument due to sudden change of measured quantity can take different forms according to the relation between capacitances that have to be filled, inertia elements and damping elements.

When inertia elements are small enough to be negligible, we get first order response which is due to filling the capacitances in the system through finite channels. The curve of change of indication with time in that case is an exponential curve. (Refer Fig. 1.1)

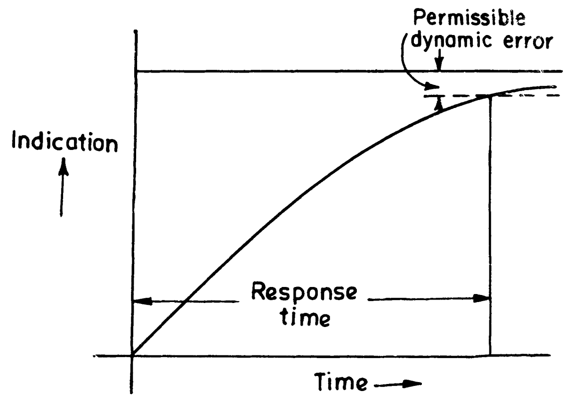


Fig. 1.1. First order response of an instrument.

If the inertia forces are not negligible, we get second order response. There are three possi-bilities of response (Refer Fig. 1.2.) according to the ratio of damping and inertia forces as follows :

— *overdamped system*—where the final indication is approached exponentially from one side.

— *under-damped system*—where the pointer approaches the position corresponding to final reading, passes it and makes a number of oscillations around it before it stops.

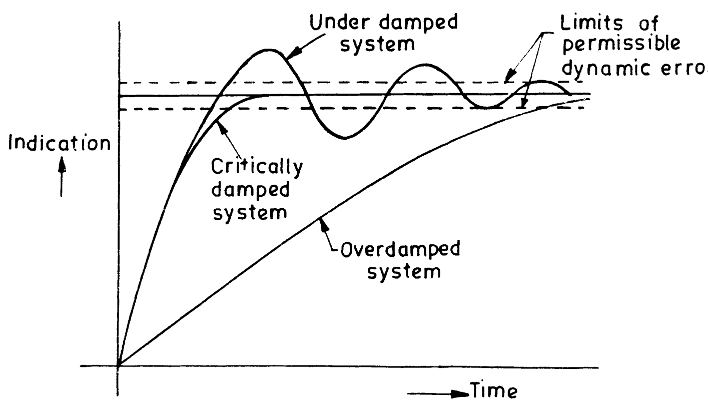


Fig. 1.2. Second order response of an instrument.

— *critically damped system*—where the pointer motion is aperiodic but quicker than in the case of overdamped system.

In all these cases the response time is determined by the inter-section of one (or two) lines surrounding the final indication line at a distance equal to the permissible value of dynamic error with the response curve of the instrument.

1.4.7. Repeatability. It is the ability of the measuring instrument to give the same value every time the measurement of a given quantity is repeated.

Any measurement process effected using a given instrument and method of measurement is subject to a large number of sources of variation like environmental changes, variability in operator performance and in instrument parameters. The repeatability is charactersied by the dispersion of indications when the same quantity is repeatedly measured. The dispersion is described by two limiting values or by the standard deviation.

The conditions under which repeatability is tested have to be specified.

1.4.8. Bias. It is the characteristic of a measure or a measuring instrument to give indications of the value of a measured quantity whose average differs from the true value of that quantity.

Bias error is due to the algebraic summation of all the systematic errors affecting the indication of the instrument. Sources of bias are maladjustment of the instrument, permanent set, non-linearly errors, errors of material measures etc.

1.4.9. Inaccuracy. It is the total error of a measure or measuring instrument under specified conditions of use and including bias and repeatability errors.

Inaccuracy is specified by two limiting values obtained by adding and subtracting to the bias error the limiting value of the repeatability error.

If the known systematic errors are corrected, the remaining inaccuracy is due to the random errors and the residual systematic errors that also have a random character.

This inaccuracy is called the "uncertainty of measurement".

1.4.10. Accuracy Class. Measuring instruments are classified into accuracy classes according to their metrological properties. There are two methods used in practice for classifying instruments into accuracy classes.

1. The accuracy class may be expressed simply by a class ordinal number that gives an idea but no direct indication of the accuracy (*e.g.* block gauges of accuracy class, 0, 1, 2 etc.).

2. The accuracy class is expressed by a number stating the maximum permissible inaccuracy as %age of the highest indication given by the instrument (*e.g.* an instrument of accuracy class 0.2 and maximum capacity 0—100 will have a maximum permissible inaccuracy of ± 0.2 at any point in the scale of instrument.

1.4.11. Precision and Accuracy. Both these terms are associated with the measuring process. Precision is defined as the repeatability of a measuring process, while accuracy is the agreement of the result of a measurement with the true value of the measured quantity. In most measurements it is the precision which is of greater importance. The chief concern is with comparing the dimension of measurement relative to each other, it being assumed that the scale used for measurement is a standard and accepted one. This would be clear from the example given below.

If a carpenter had to cut a board to fit the shelf into two projections in the wall, it does not matter whether his scale is accurate or not, provided he uses the same scale for the measurement of board and the distance between projections in the wall. Here the precision with which he measures two is of importance.

Now supposing he had to order for the board from market then it is necessary that the scale used by him and the one in market are in agreement with each other. One way to achieve this is

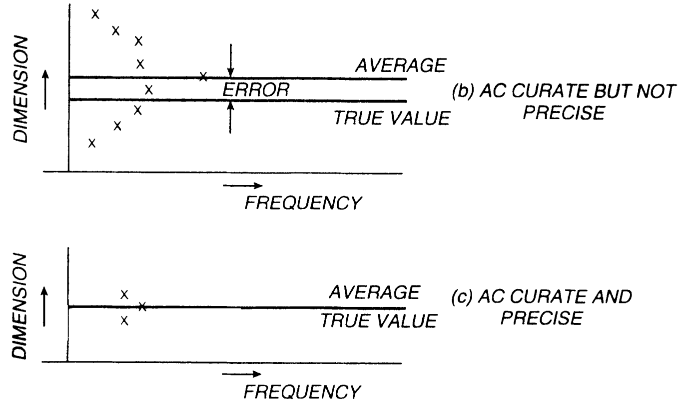


Fig. 1.3

Illustrating distinction between accuracy and precision by measuring a component several times and plotting the readings, by three instruments : (a) precise but not accurate, (b) accurate but not precise, (c) accurate and precise.

that both use the accurate scales in accordance with the standard scales. In this case, accuracy of the scale is important and it should be manufactured such that its units are in accordance with the standard units set.

The distinction between the precision and accuracy will become clear by the following example (shown in Fig. 1.3), in which several measurements are made on a component by different types of instruments and results plotted.

From Fig. 1.3, it will be obvious that precision is concerned with a process or a set of measurements, and not a single measurement. In any set of measurements, the individual measurements are scattered about the mean, and the precision tells us to how well the various measurements performed by same instrument on the same component agree with each other. It will be appreciated that poor repeatability is a sure sign of poor accuracy. Good repeatability of the instrument is a necessary but not a sufficient condition of good accuracy. Accuracy can be found by taking root mean square of repeatability and systematic error *i.e.*

$$\text{Accuracy} = \sqrt{(\text{repeatability})^2 + (\text{systematic error})^2}.$$

Error is the difference between the mean of set of readings on same component and the true value. Less is the error, more accurate is the instrument. Since the true value is never known, uncertainty creeps in, and the magnitude of error must be estimated by other means. The estimate of uncertainty of a measuring process can be made by taking care of systematic and constant errors, and other contributions to the uncertainty due to scatter of the results about the mean.

So wherever great precision is required in manufacture of mating components, they are manufactured in a single plant, where measurements are taken with same standards and internal measuring precision can achieve the desired results. If they are to be manufactured in different plants and subsequently assembled in another, the accuracy of the measurement of two plants with true standard value is important.

1.4.12. Accuracy. In mechanical inspection, the accuracy of measurement is the most important aspect. The accuracy of an instrument is its ability to give correct results. It is, therefore, better to understand the various factors which affect it and which are affected by it. The accuracy of measurement to some extent is also dependent upon the sense of hearing or sense of touch or sense of sight, *e.g.*, in certain instrument the proportions of sub-divisions have to be estimated by the sense of sight ; of course, in certain instances the vernier device may be employed in order to substitute the 'estimation of proportion' by 'recognition of coincidence'. In certain instruments, accuracy of reading depends upon the recognition of a threshold effect, *i.e.* whether the pointer is "just moving, or 'just not moving'.

One thing is very certain that there is nothing like absolute or perfect accuracy and there is no instrument capable of telling us, whether or not we have got it. The phrases like 'dead accurate' or 'dead right' become meaningless and of only relative value. In other words, no measurement can be absolutely correct ; and there is always some error, the amount of which depends upon the accuracy and design of the measuring equipment employed and the skill of the operator using it, and upon the method adopted for the measurement. In some instruments, accuracy depends upon the recognition of a threshold effect. In some instruments, proportions of sub-divisions have to be estimated. In such cases, skill of operator is responsible for accuracy, Parallax is also very common and can be taken care of by installing a mirror below the pointer. How method of measurement affect accuracy would be realised in angle measurement by sine bar, *i.e.* large errors may occur when sine bar is intended to be used for measuring large angles. Apparatus and methods should be designed so that errors in the final results are small compared with errors in actual measurements made. The equipment chosen for a particular measurement must bear some relation to the desired accuracy in the result, and as a general rule, an instrument which can be read to the next decimal place beyond that required in the measurement should be used, *i.e.*, if a measurement is desired to an accuracy of 0.01 mm, then instrument with accuracy of 0.001 mm should be used for this purpose.

When attempts are made to achieve higher accuracy in the measuring instruments, they become increasingly sensitive. But an instrument can't be more accurate than is permitted by degree of sensitiveness, the sensitivity being defined as the ratio of the change of instrument indication to the change of quantity being measured. It may be realized that the degree of sensitivity of an instrument is not necessarily the same all over the range of its readings. Another important consideration for achieving higher accuracy is that the readings obtained for a given quantity should be same all the time, *i.e.* in other words the readings should be consistent. A highly sensitive instrument is not necessarily consistent in its readings and, clearly, an inconsistent instrument can't be accurate to a degree better than its inconsistency. It may also be remembered that the range of measurement usually decreases as the magnification increases and the instrument may be more affected by temperature variations and be more dependent upon skill in use.

Thus, it is true to say that a highly accurate instrument possesses both greater sensitivity and consistency. But at the same time an instrument which is sensitive and consistent need not necessarily be accurate because the standard from which its scale is calibrated may be wrong. (It is, of course, presupposed that there always exists an instrument whose accuracy is greater than the one with which we are concerned). In such an instrument, the errors will be constant at any given reading and therefore, it would be quite possible to calibrate it.

It is very obvious that higher accuracy can be achieved by incorporating the magnifying devices in the instrument, and these magnifying devices carry with them their own inaccuracies, *e.g.*, in an optical system the lens system may distort the ray in a variety of ways and the success of the system depends upon the fidelity with which the lens system can produce the magnified images etc. In mechanical system the errors are introduced due to bending of levers, backlash at the pivots, inertia of the moving parts, errors of the threads of screws etc. Probably the wrong geometric design may also introduce errors. By taking many precautions we can make these errors extremely small, but, the smaller we try to make them, the greater becomes the complication of our task, and with this increased complication, the greater the number of possible sources of error which we must take care of. Thus the greater the accuracy is aimed at, greater the number of sources of errors to be investigated and controlled. As regards the instrumental errors, they can be kept as small as possible. The constant or knowable sources of errors can be determined by the aid of superior instruments and the instrument may be calibrated accordingly. The variable or unknowable sources of errors make the true value lie within plus or minus departure from the observed value and can't be tied down more closely than that. However, an accurate measuring instrument should fulfil the following requirements :

(*i*) It should possess the requisite and constant accuracy.

(*ii*) As far as possible, the errors should be capable of elimination by adjustment contained within the instrument itself.

(*iii*) Every important source of inaccuracy should be known.

(*iv*) When an error can't be eliminated, it should be made as small as possible.

(*v*) When an error can't be eliminated, it should be capable of measurement by the instrument itself and the instrument calibrated accordingly.

(*vi*) As far as possible the principle of similarity must be followed, *i.e.* the quantity to be measured must be similar to that used for calibrating the instrument. Further the measuring operations performed on the standard and on the unknown must be as identical as feasible and under the same physical conditions (environment temperature, etc. and using the same procedures in all respects in both the cases of calibration and measurement).

In some instruments, accuracy is expressed as percentage of full scale deflection, *i.e.* percentage of maximum reading of instrument. Thus at lower readings in the range, accuracy may be very poor. The range of such instruments should be selected properly so that the measured value is at about 70-90% of the full range.

Accuracy in measurement is essential at all stages of product development from research to development and design, production, testing and evaluation, quality assurance, standardisation, on-line control, operational performance appraisal, reliability estimation, etc.

The last word in connection with accuracy is that the accuracy at which we aim, that is to say, the trouble we take to avoid errors in manufacture and in measuring those errors during inspection must depend upon the job itself and on the nature of what is required, *i.e.* we should make ourselves very sure whether we want that much accuracy and that cost to achieve it will be compensated by the purpose for which it is desired.

1.4.13. Accuracy and Cost. The basic objective of metrology should be to provide the accuracy required at the most economical cost. The accuracy of measuring system includes elements such as :

(*a*) Calibration Standards,

(*b*) Workpiece being measured,

(*c*) Measuring Instruments

(*d*) Person or Inspector carrying out the measurement, and

(*e*) Environmental influences.

The above arrangement and analysis of the five basic Metrology elements can be composed into the acronym SWIPE for convenient reference :

S = Standard, W = Workpiece, I = Instrument, P = Person and E = Environment.

Higher accuracy can be achieved only if, all the sources of errors due to the above five elements in the measuring system be analysed and steps taken to eliminate them. An attempt is made here to summarise the various factors affecting these five elements.

1. *Standard.*It may be affected by ambient influences (thermal expansion), stability with time, elastic properties, geometric compatibility, and position of use.

2. *Workpiece*, itself may be affected by ambient influences, cleanliness, surface condition, elastic properties, geometric truth, arrangement of supporting it, provision of defining datum etc.

3. *Instrument* may be affected by hysteresis, backlash, friction, zero drift error, deformation in handling or use of heavy workpieces, inadequate amplification, errors in amplification device, calibration errors, standard errors, correctness of geometrical relationship of workpiece and standard, proper functioning of contact pressure control, mechanical parts (slides, ways, or moving elements) working efficiently, and repeatability adequacy etc.

4. *Personal* errors can be many and mainly due to improper training in use and handling, skill, sense of precision and accuracy appreciation, proper selection of instrument, attitude towards and realisation of personal accuracy achievements, etc.

5. *Environment* exerts a great influence. It may be affected by temperature ; thermal expansion effects due to heat radiation from light, heating of components by sunlight and people, temperature equalisation of work, instrument and standard ; surroundings ; vibrations ; lighting ; pressure gradients (affect optical measuring systems) etc.

The design of measuring systems involves proper analysis of cost-to-accuracy consideration and the general characteristics of cost and accuracy appears to be as shown in Fig. 1.4.

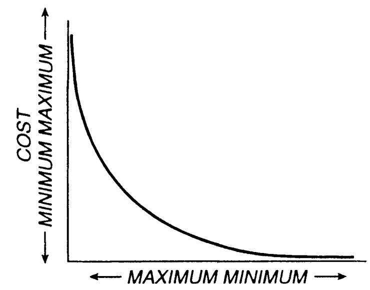


Fig. 1.4

It will be clear from the graph that the cost rises exponentially with accuracy. If the measured quantity relates to a tolerance (*i.e.* the permissible variation in the measured quantity), the accuracy objective should be 10% or slightly less of the tolerance. In a few cases, because of technological limitations, the accuracy may be 20% of the tolerance ; because demanding too high accuracy may tend to make the measurement unreliable. In practice, the desired ratio of accuracy to tolerance is decided by considering the factors such as the cost of measurement versus quality and the reliability criterion of the product.

1.4.14. Magnification. The human limitations or incapability to read instruments places limit on sensitiveness of instruments. Magnification (or amplification) of the signal from measuring instrument can make it better readable. The magnification is possible on mechanical, pneumatic, optical, electrical principles or combinations of these.

Magnification by mechanical means is the simplest and costwise most economical method. The various methods of mechanical magnification are based on the principles of lever, wedge, gear train etc.

In the case of magnification by wedge method, magnification is equal to tan θ, where θ is the angle of wedge.

Mechanical magnification method is usually grouped with other type of magnification methods to combine their merits.

Optical magnification is based on the principle of reflection by tilting a mirror, or on projection technique. In the case of reflection by a mirror, the angular magnification is 2 because the reflected ray is tilted by twice the angle of tilt of mirror. With 2-mirror system four-fold magnification is obtained.

In the case of optical lever magnification, various features of the test specimen are established on projector screen using reference lines as datum. Very high magnifications are possible in such systems.

Pneumatic magnification method is ideally suited for internal measurement. It offers better reliability and stability. Very high magnifications (upto 30,000 : 1) are possible.

Electrical magnification methods have the advantages of better control on the amount of magnification, quick response, large range of linearity, etc. Electrical magnification is based on sensing change in inductance or capacitance, which is measured by a wheatstone bridge.

Electronic method of magnification is more reliable and accurate. Electronic methods are ideally suited for processing of signals, *viz.* amplification, filtering, validation of signal, sensing for high and low limits, autocalibration, remote control telemetry etc.

1.4.15. Repeatability. Repeatability is the most important factory in any measuring system as it is the characteristics of the measuring system whereby repeated trials of identical inputs of measured value produce the same indicated output from the system.

It is defined as the ability of a measuring system to reproduce output readings when the same measurand value is applied to it consecutively, under the same conditions, and in the same direction. It could be expressed either as the maximum difference between output readings, or as "within ... per cent of full scale output."

Repeatability is the only characteristic error which cannot be calibrated out of the measuring system. Thus repeatability becomes the limiting factor in the calibration process, thereby limiting the overall measurement accuracy. In effect, repeatability is the minimum uncertainty in the comparison between measurand and reference.

1.4.16. Uncertainty. It is the range about the measured value within which the true value of the measured quantity is likely to lie at the stated level of confidence. It can be calculated when the trade or population standard deviation is known or it can be estimated from the standard deviation calculated from finite number of observation having normal distribution.

1.4.17. Confidence levels. It is the measure of a degree of reliability with which the results of measurement can be expressed. Thus if u be uncertainty in a measured quantity x at 98% confidence level, then the probability for true value to lie between $x + u$ and $x - u$ is 98%. Thus on measuring this quantity a large number of times, then 98% of the values will lie in between $x + u$ and $x - u$.

1.4.18. Calibration. The calibration of any measuring system is very important to get meaningful results. In case where the sensing system and measuring system are different, then it is imperative to calibrate the system as an integrated whole in order to take into account the error producing properties of each component. Calibration is usually carried out by making adjustments such that readout device produces zero output for zero-measurand input, and similarly it should display an output equivalent to the known measurand input near the full-scale input value.

It is important that any measuring system calibration should be performed under environmental conditions that are as close as possible to those conditions under which actual measurements are to be made.

It is also important that the reference measured input should be known to a much greater degree of accuracy—usually the calibration standard for the system should be at least one order of magnitude more accurate than the desired measurement system accuracy, *i.e.* accuracy ratio of 10 : 1.

1.4.19. Calibration vs. Certification. Calibration is the process of checking the dimensions and tolerances of a gauge, or the accuracy of a measurement instrument by comparing it to a like instrument/gauge that has been certified as a standard of known accuracy. Calibration is done by detecting and adjusting any discrepancies in the instrument's accuracy to bring it within acceptable limits. Calibration is done over a period of time, according to the usage of the instrument and the materials of its parts. The dimensions and tolerances of the instrument/gauge are checked to determine whether it has departed from the previously accepted certified condition. If departure is within limits, corrections are made. If deterioration is to a point that requirements can't be met any more then the instrument/gauge can be downgraded and used as a rough check, or it may be reworked and recertified, or be scrapped. If a gauge is used frequently, it will require more maintenance and more frequent calibration.

Certification is performed prior to use of instrument/gauge and later to reverify if it has been reworked so that it again meets its requirements. Certification is given by a comparison to a reference standard whose calibration is traceable to an accepted national standard. Further such reference standards must have been certified and calibrated as master not more than six months prior to use.

1.4.20. Sensitivity and Readability. The terms "sensitivity" and "readability" are often confused with accuracy and precision. Sensitivity and readability are primarily associated with equipment while precision and accuracy are associated with the measuring process. It is not necessary that the most sensitive or the most readable equipment will give most precise or the most accurate results.

Sensitivity refers to the ability of a measuring device to detect small differences in a quantity bein measured. It may so happen that high sensitivity instrument may lead to drifts due to thermal or other effects, so that its indications may be less repeatable or less precise than those of the instrument of lower sensitivity.

Readability refers to the susceptibility of a measuring device to having its indications converted to a meaningful number. A micrometer instrument can be made more readable by using verniers. Very finely spaced lines may make a scale more readable when a microscope is used, but for the unaided eye, the readability is poor.

1.4.21. Uncertainty in Measurement. Whenever a value of physical quantity is determined through a measurement process, some errors are inherent in the process of measurement and it is only the best estimate value of the physical quantity obtained from the given experimental data. Thus quantifying a measurable quantity through any measurement process is meaningful only if the value of the quantity measured with a proper unit of measurement is accompanied by an overall uncertainty of measurement. It has two components arising due to random errors and systematic errors. Uncertainty in measurement could be defined as that part of the expression of the result of a measurement which states the range of values within which the true value, or if appropriate, the conventional true value is estimated to lie. In cases where there is adequate information based on a statistical distribution, the estimate may be associated with a specified probability. In other cases, an alternative form of numerical expression of the degree of confidence to be attached to the estimate may be given.

1.4.22. Random uncertainty and Systematic uncertainty. Random uncertainty is that part of uncertainty in assigning the value of a measured quantity which is due to random errors. The value of the random uncertainty is obtained on multiplication of a measure of the random errors which is normally the standard deviation by a certain factor '*t*'. The factor '*t*' depends upon the sample size and the confidence level. Systematic uncertainty is that part of uncertainty which is due to systematic errors and cannot be experimentally determined unless the equipment and environmental conditions are changed. It is obtained by suitable combination of all systematic errors arising due to different components of the measuring system.

It is necessary to understand difference between systematic uncertainty and correction.

The calibration certificate of an instrument gives a correspondence between its indication and the quantity it is most likely to measure. The difference between them is the correction which is to be invariably applied. However, there will be an element of doubt in the value of the correction so stated. This doubt is quantitatively expressed as accuracy or overall uncertainty in assigning the value to the correction stated and will be one component of the systematic uncertainty of that instrument. For example, in case of a metre bar, the distance between the zero and 1,000 mm graduation marks may be given as 1000.025 ± 0.005 mm. Then 0.025 mm is the correction and 0.005 mm is the component of systematic uncertainty of the metre bar.

1.4.23. Traceability. This is the concept of establishing a valid calibration of a measuring instrument or measurement standard by step-by-step comparison with better standards up to an accepted or specified standard. In general, the concept of traceability implies eventual reference to an appropriate national or international standard.

1.4.24. Fiducial Value. A prescribed value of a quantity to which reference is made, for example, in order to define the value of an error as a proportion of this prescribed value.

1.5. Selection of Instruments

The important characteristics to be considered in selection of an instrument are its measuring range, accuracy and precision. Usually accuracy is poor at the lower end of scale which should be avoided. In such a situation, where accurate measurement is required throughout full range, two instruments with different ranges may be used, one for lower range and other for full range.

The precision of instrument is very important feature since it should give repeatable readings which is possible with precise instrument. If an instrument is precise then accuracy can be taken care of by proper calibration of the instrument. It may be mentioned that accuracy is affected by systematic errors which can be accounted for.

Resolution or sensitivity, *i.e.* discrimination or relation between the movement of pointer and corresponding change in the measured quantity is also important aspect. It represents a smallest change in the measured quantity which produces a perceptible movement of the pointer.

1.6. Classification of Methods of Measurements

In precision measurements various methods of measurement are followed depending upon the accuracy required and the amount of permissible error.

There are numerous ways in which a quantity can be measured. Any method of measurement should be defined in such a detail and followed by such a standard practice that there is little scope for uncertainty. The nature of the procedure in some of the most common measurements is described below. Actual measurements may employ one or more combinations of the following.

(*i*) *Direct method of measurement.* In this method the value of a quantity is obtained directly by comparing the unknown with the standard. It involves, no mathematical calculations to arrive at the results, for example, measurement of length by a graduated scale. The method is not very accurate because it depends on human insensitiveness in making judgement.

(*ii*) *Indirect method of measurement.* In this method several parameters (to which the quantity to be measured is linked with) are measured directly and then the value is determined by mathematical relationship. For example, measurement of density by measuring mass and geometrical dimensions.

(*iii*) *Fundamental method of measurement.* Also known as the *absolute method of measurement*, it is based on the measurement of the base quantities used to define the quantity. For example, measuring a quantity directly in accordance with the definition of that quantity, or measuring a quantity indirectly by direct measurement of the quantities linked with the definition of the quantity to be measured.

(*iv*) *Comparison method of measurement.* This method involves comparison with either a known value of the same quantity or another quantity which is function of the quantity to be measured.

(*v*) *Substitution method of measurement.* In this method, the quantity to be measured is measured by direct comparison on an indicating device by replacing the measuring quantity with some other known quantity which produces same effect on the indicating device. For example, determination of mass by Borda method.

(*vi*) *Transposition method of measurement.* This is a method of measurement by direct comparison in which the value of the quantity to be measured is first balanced by an initial known value A of the same quantity ; next the value of the quantity to be measured is put in the place of that known value and is balanced again by a second known value B. When the balance indicating device gives the same indication in both cases, the value of the quantity to be measured is $\sqrt{AB}$. For example, determination of a mass by means of a balance and known weights, using the Gauss double weighing method.

(*vii*) *Differential or comparison method of measurement.* This method involves measuring the difference between the given quantity and a known master of near about the same value. For example, determination of diameter with master cylinder on a comparator.

(*viii*) *Coincidence method of measurement.* In this differential method of measurement the very small difference between the given quantity and the reference is determined by the observation of the coincidence of scale marks. For example, measurement on vernier caliper.

(*ix*) *Null method of measurement.* In this method the quantity to be measured is compared with a known source and the difference between these two is made zero.

(*x*) *Deflection method of measurement.* In this method, the value of the quantity is directly indicated by deflection of a pointer on a calibrated scale.

(*xi*) *Interpolation method of measurement.* In this method, the given quantity is compared with two or more known value of near about same value ensuring at least one smaller and one bigger than the quantity to be measured and the readings interpolated.

(*xii*) *Extrapolation method of measurement.* In this method, the given quantity is compared with two or more known smaller values and extrapolating the reading.

(*xiii*) *Complimentary method of measurement.* This is the method of measurement by comparison in which the value of the quantity to be measured is combined with a known value of the same quantity so adjusted that the sum of these two values is equal to predetermined comparison value. For example, determination of the volume of a solid by liquid displacement.

(*xiv*) *Composite method of measurement.* It involves the comparison of the actual contour of a component to be checked with its contours in maximum and minimum tolerable limits. This method provides for the checking of the cumulative errors of the interconnected elements of the component which are controlled through a combined tolerance. This method is most reliable to ensure inter-changeability and is usually effected through the use of composite "Go" gauges, for example, checking of the thread of a nut with a screw plug "GO" gauge.

(*xv*) *Element method.* In this method, the several related dimensions are gauged individually, *i.e.* each component element is checked separately. For example, in the case of thread, the pitch diameter, pitch, and flank angle are checked separately and then the virtual pitch diameter is calculated. It may be noted that value of virtual pitch diameter depends on the deviations of the above thread elements. The functioning of thread depends on virtual pitch diameter lying within the specified tolerable limits.

In case of composite method, all the three elements need not be checked separately and is thus useful for checking the product parts. Element method is used for checking tools and for detecting the causes of rejects in the product.

(*xvi*) *Contact and contactless methods of measurements.* In contact methods of measurements, the measuring tip of the instrument actually touches the surface to be measured. In such cases, arrangements for constant contact pressure should be provided in order to prevent errors due to excess contact pressure. In contactless method of measurements, no contact is required. Such instruments include tool-maker's microscope and projection comparator, etc.

For every method of measurement a detailed definition of the equipment to be used, a sequential list of operations to be performed, the surrounding environmental conditions and descriptions of all factors influencing accuracy of measurement at the required level must be prepared and followed.

1.6.1. Classification of Measuring Instruments. According to the functions, the measuring instruments are classified as :

(1) Length measuring instruments.

(2) Angle measuring instruments.

(3) Instruments for checking the deviations from geometrical forms.

(4) Instruments for determining the quality of surface finish.

According to the accuracy of measurement, the measuring instruments are classified as follows :

(1) Most accurate instruments *e.g.*, light-interference instruments.

(2) Second group consists of less accurate instruments such as tool room microscopes, comparators, optimeters etc.

(3) The third group comprises still less accurate instruments *e.g.*, dial indicators, vernier calipers and rules with vernier scales.

1.6.2. Metrological characteristics of Measuring Instruments. Measuring instruments are usually specified by their metrological properties, such as range of measurement, scale graduation value, scale spacing, sensitivity and reading accuracy.

Range of Measurement. It indicates the size values between which measurements may be made on the given instrument.

Scale range. It is the difference between the values of the measured quantities corresponding to the terminal scale marks.

Instrument range. It is the capacity or total range of values which an instrument is capable of measuring. For example, a micrometer screw gauge with capacity of 25 to 50 mm has instrument range of 25 to 50 mm but scale range is 25 mm.

Scale Spacing. It is the distance between the axes of two adjacent graduations on the scale. Most instruments have a constant value of scale spacing throughout the scale. Such scales are said to be linear.

In case of non-linear scales, the scale spacing value is variable within the limits of the scale.

Scale Division Value. It is the measured value of the measured quantity corresponding to one division of the instrument, *e.g.*, for ordinary scale, the scale division value is 1 mm. As a rule, the scale division should not be smaller in value than the permissible indication error of an instrument.

Sensitivity (Amplication or gearing ratio). It is the ratio of the scale spacing to the division value. It could also be expressed as the ratio of the product of all the larger lever arms and the product of all the smaller lever arms. It is the property of a measuring instrument to respond to changes in the measured quantity.

Sensitivity Threshold. It is defined as the minimum measured value which may cause any movement whatsoever of the indicating hand. It is also called the discrimination or resolving power of an instrument and is the minimum change in the quantity being measured which produces a perceptible movement of the index.

Reading Accuracy. It is the accuracy that may be attained in using a measuring instrument.

Reading Error. It is defined as the difference between the reading of the instrument and the actual value of the dimension being measured.

Accuracy of observation. It is the accuracy attainable in reading the scale of an instrument. It depends on the quality of the scale marks, the width or the pointer/index, the space between the pointer and the scale, the illumination of the scale, and the skill of the inspector. The width of scale mark is usually kept one-tenth of the scale spacing for accurate reading of indications.

Parallax. It is apparent change in the position of the index relative to the scale marks, when the scale is observed in a direction other than perpendicular to its plane.

Repeatability. It is the variation of indications in repeated measurements of the same dimension. The variations may be due to clearances, friction and distortions in the instrument's mechanism. Repeatability represents the reproducibility of the readings of an instrument when a series of measurements in carried out under fixed conditions of use.

Measuring force. It is the force produced by an instrument and acting upon the measured surface in the direction of measurement. It is usually developed by springs whose deformation and pressure change with the displacement of the instrument's measuring spindle.

1.7. The Measurement Problem

In practice, we come across four basic conditions to be controlled by tolerances, *viz*, (*a*) size, (*b*) form, (*c*) location and (*d*) conditions of assembly, operation, or function. Fig. 1.5 illustrates these. The difference between sizes X and Y determines the assembly condition. Size conditions are generally simple to specify and control ; the form and location conditions are more complex, especially where composite surfaces and cumulative tolerances are involved. It will be appreciated that all these four conditions inter-relate to define quality characteristics, and the problem of measuring quality characteristics to evaluate conformance to specifications becomes complex. Lack of true geometric perfection makes it difficult to define and control product quality characteristics. It may be noted that it is easy to define geometric form but difficult to produce. However, to maintain specific quality, the variation from perfect form must be defined and controlled. The geometric variations known as macro-errors concern straightness, flatness, parallelism, squareness, angular displacement, symmetry, concentricity, eccentricity, roundness. Lack of perfect rigidity caused due to material properties like expansion, stretching, springing, warping etc., also affect geometric form, size and location conditions.

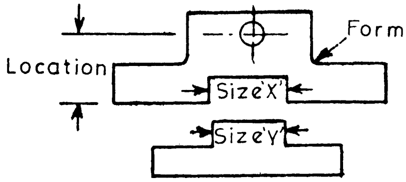


Fig. 1.5. Product conditions.

The inter-relationships of size, form and location conditions required to define quality characteristics, coupled with production variations due to geometric form and rigidity errors, lead to a variety of complex measurement problems involving sophisticated gauging method.

In some cases the configuration of parts is such that accurate measurement becomes difficult. In some cases, it is not possible for the standard gauge or tool to span the component. Such cases are : parts having not even a single common plane, irregular curved surfaces, odd number spline or gear, parts with phantom dimensions (*i.e.*, dimensions to be gauged have to be calculated or their dimensions are w.r.t. points in space) etc.

The measurement must be correct to a degree commensurate with the specified tolerances and the required functional service of the product. Following two factors need to be considered when evaluating the correctness of dimensional measurements : (*i*) gauging accuracy, (*ii*) the proper location of the measured dimension on the physical part. It must be remembered that the improperly located dimensions, can often have a greater effect on correctness of dimensional measurements than errors due to insufficient indicating accuracy.

The precision of the measurement can be affected by limitations in either of the basic requirements, *viz.* the accuracy of the instrument at the proper location of the gauging points which determine the dimension being measured on the physical part.

1.8. General Care of Metrological Equipment

The equipment (apparatus) used for precision measurements is designed to fine limits of accuracy and is easily liable to be damaged by even slight mishandling and such damage may not be noticeable. A great deal of careful handling is, therefore, required. As far as possible, the highly finished surfaces should not be touched by hand because the natural acids on the skin are likely to corrode the finished surface and also the temperature of body may upset the dimensions of the precision instruments. In order to overcome this many standard metrology laboratories recommend washing of hands thoroughly and coating them with a thin film of pure petroleum jelly before handling the instruments. Further very precise equipment like slip gauges is allowed to be handled only by using a piece of chamois leather or tongs made from a strip of "Perspex".

When the equipment is not in use, it should be protected from atmospheric corrosion. For this purpose, the highly finished surfaces are first wiped with a solvent to remove any finger marks and then coated with mixture of heated petroleum jelly and petrol. This mixture spreads much more easily and is applied with cloth or with fingers. Brushing is not recommended as it is liable to trap air which, with the moisture it contains, may cause rusting.

As the standard temperature for measurement is 20°C, for very precise measurements the instruments and workpieces should be allowed to attain this temperature before use and the handling should be as little as possible.

1.9. Objectives of Metrology

While the basic objective of a measurement is to provide the required accuracy at minimum cost, metrology would have further objective in a modern engineering plant with different shops like Tool Room, Machine Shop, Press Shop, Plastic Shop, Pressure Die Casting Shop, Electroplating and Painting Shop, and Assembly Shop, as also Research, Development and Engineering Department. In such an engineering organisation, the further objectives would be as follows :

(*a*) Thorough evaluation of newly developed products, to ensure that components designed are within the process and measuring instrument capabilities available in the plant.

(*b*) To determine the process capabilities and ensure that these are better than the relevant component tolerances.

(*c*) To determine the measuring instrument capabilities and ensure that these are adequate for their respective measurements.

(*d*) To minimise the cost of inspection by effective and efficient use of available facilities, and to reduce the cost of rejects and rework through application of Statistical Quality Control Techniques.

(*e*) *Standardisation of measuring methods.* This is achieved by laying down inspection methods for any product right at the time when production technology is prepared.

(*f*) *Maintenance of the accuracies of measurement.* This is achieved by periodical calibration of the metrological instruments used in the plant.

(*g*) Arbitration and solution of problems arising on the shop floor regarding methods of measurement.

(*h*) Preparation of designs for all gauges and special inspection fixtures.

1.10. Requirements of an Inspection Tool

The requirements of an ideal inspection tool are : It should be

(*a*) accurate

(*b*) require a minimum of operator skill

(*c*) inspect a specific type of error

(*d*) fast to use

(*e*) Self checking.

The degree of accuracy of calibration depends on the accuracy of the inspecting instruments. Devices which reduce dependence on operator skill contribute to both efficiency and accuracy. The requirement of speed is not for economic reasons but to avoid errors from changes in temperature where inspections become involved. A good inspection tool should be capable of being checked against itself. This feature increases the reliability.

1.11. Standardisation and Standardising Organisations

For overall higher economy, efficiency and productivity in a factory and country, it is essential that diversity be minimised and interchangeability among parts encouraged. All this is possible with standardisation. Standardisation is done at various levels, *viz.* International, National, Association, Company.

Realising the role of standardisation in the development of industry, organisations to handle the complexities of standardisation have been evolved in each of the chief industrial countries. In India, Bureau of Indian Standards (BIS) is responsible for evolving standards on metrological instruments, etc. There are several sectional committees, each dealing with various main branches of industry, in BIS. The detailed work of drawing up specifications is done by more specialised technical committees who prepare a draft standard based on practice in other countries and the needs of the country, and circulate it to relevant industries, government and service departments, research and teaching organisations, and others likely to be interested. Comments are invited both from producer and user to consider all aspects ; meetings help to discuss the matters in depth and final standards issued. The technical committees also keep on revising the existing standards from time to time.

The Bureau of Indian Standards is the National body for standardisation in India.

The functions of the Bureau are :

(*a*) Formulation, publication and promotion of Indian Standards ;

(*b*) Inspection of articles or process under Certification Scheme ;

(*c*) Establishment, maintenance and recognition of laboratories ;

(*d*) Formulate, implement and coordinate activities relating to quality maintenance and improvement in products and processes ;

(*e*) Promote harmonious development in standardization, quality systems and certification and matters connected therewith both within the country and at international level ;

(*f*) Provide information, documentation and other services tc consumers and recognised consumer organisations on such terms and conditions as may be mutually agreed upon ;

(*g*) Give recognition to quality assurance systems in manufacturing or processing units on such terms and conditions as mutually agreed upon ;

(*h*) Bring out handbooks, guides and other special publications ; and for conformity to any other standard if so authorized.

Thus, the main functions of the Bureau can be grouped under standards formulation, certification marking and laboratory testing, promotional and international activities.

Bureau of Indian Standards has under the Mechanical Engineering Division Council, EDC, a separate Engineering Metrology Sectional Committee. This Committee was set up in 1958 and its main task is to formulate standards for the various aspects of dimensional metrological measuring instruments and accessories used in the mechanical engineering field. A large number of Indian Standards in the field of engineering metrology have been formulated.

In Great Britain, British Standards Institution plays similar role to BIS.

In Europe, the International Federation of National Standardising Association, known as I.S.A., co-ordinates the work of the continental countries. Before Second World War, U.K. and U.S.A. did not take any part in it, but after war, the countries like U.K., U.S.A. and Russia have taken part in its works. In 1946, the I.S.A., was re-formed as the International Organisation for Standardisation, I.S.O. In fact, for engineering matters, the foremost standards organisation at international level is I.S.O. The national standards organisation of individual countries are the members of I.S.O. The I.S.O. recommendations are used as basis for national and company standards. Lot of co-operative discussions in the field of standardisation have also been carried out in three countries—America, Britain and Canada known was ABC conference. The International Electro-technical Commission (IEC) deals with electrical engineering standards. Both ISO and IEC have published recommendations on some aspects of engineering metrology.

National Physical Laboratories (NPL) carry out lot of research work in various fields ; responsible for defining standards, and also issue certification marks for quality instruments.

1.11.1. International Organisation of Weights and Measures. It was established in 1975 under the "International Metre Convention" in Paris with the object of maintaining uniformity of measurements throughout the world. It comprises of :

(*a*) The General Conference of Weights and Measures.

(*b*) The International Committee of Weights and Measures.

(*c*) The International Organisation of Legal Metrology.

1.11.2. General Conference of Weights and Measures. Its objects are :

(*i*) To draw up and promote the decisions necessary for the propagation and perfection of an international system of units and standards of measurement.

(*ii*) To approve the results of new fundamental metrological determinations and the various scientific resolutions in the field of metrology which are of international interest.

1.11.3. International Committee of Weights and Measures. This Committee is placed under the authority of the General Conference of Weights and Measures and is responsible for promoting the decisions taken by the latter. Its objects are :

(*i*) To direct and supervise the work of the International Bureau of Weights and Measures.

(*ii*) To establish co-operation among national laboratories of metrology for executing the metrological work which the General Conference of Weights and Measures decides to execute jointly by the member states of the organisation.

(*iii*) To direct such work and co-ordinate the results and to look after the conservation of the International Standards.

1.11.4. Principal Global Organisations involved in Metrology

(*i*) **BIPM (Bureau International des Poids et Mesures).** It is created under the Metre convention for measurement standard activities. It provides leadership in ensuring collaboration on metrological matters and the maintenance of an efficient worldwide measurement system. It serves as the technical focal point to guarantee the equivalence of national standards. BIPM with its laboratories and offices at Serves act as a permanent international centre for Metrology under the supervision of the CIPM.

(*ii*) **ILAC (International Laboratory Accreditation Conference).** It is engaged in international laboratory accreditation and the standards writing bodies. It has demonstrated competence in calibration and testing.

(*iii*) **IEC (International Electrotechnical Commission).** A voluntary sector to prescribe standards.

(*iv*) **CIPM (Comite International des Poids et Mesures).** Most of the activities of CIPM are performed under the supervision of CIPM. Several (CCs) consultative committees have been set up by the CIPM.

(*v*) **CGPM (Conference Generale des Poids et Mesures).**

(*vi*) **ISO (International Organisation for Standardisation).** A voluntary sector to specify standards.

(*vii*) **NMI (National Metrology Institute).** A national laboratory responsible for the development and maintenance of measurement standards for the dissemination of the SI units, their multiples and sub multiples, and capable of making accurate measurements available to all users.

(*viii*) **International Organisation of Legal Metrology (OIML).** It was established in 1955 under the "International Convention of Legal Metrology" Paris to unify the metrological practices. Its objects are :

— To determine the general principles of Legal Metrology. Legal Metrology is concerned with the statutory technical and legal requirement of units of measurements, methods of measurements and measuring instruments with a view to assure public guarantee in respect of the security and the appropriate accuracy of measurements.

— To study with the object of unification, statutory and regulatory problems of legal metrology the solution of which is of international interest.

— To establish the draft of a model law and regulation on measuring instruments and their use.

— To prepare a plan for the physical organisation of a model service for the verification and control of measuring instruments and to establish the necessary and adequate characteristics and qualities which measuring instruments should possess in order that they may be approved by the member states and their use recommended on international basis.

This organisation comprises of the International Conference of Legal Metrology, the International Committee of Legal Metrology and the International Bureau of Legal Metrology.

OIML has made a number of international recommendations. They have also published a "Vocabulary of Legal Metrology-Fundamental Terms" the english translation of which is published in India by the Directorate of Weights and Measures, Ministry of Industry.

The functions of the Directorate of Weights and Measures are :

— to ensure the conservation of national standards and to guarantee their accuracy by comparison with international standards.

— to guarantee and impart proper accuracy to the secondary standards by comparison with national standards.

— to carry out scientific and technical work in all fields of metrology and methods of measurements.

— to take part in the work of other national organisations interested in metrology.

— to draw up draft laws relating to legal metrology and to promulgate the corresponding regulations.

— to regulate and advise on, supervise and control the manufacture and repair of measuring instruments.

— to inspect the use of instruments and the measurement operations when such use and such operations are covered under public guarantee.

— to detect frauds in measurement or sale of goods and to book offender for trials where necessary.

— to coordinate the activities of authorities exercising metrological supervision.

— cooperate with all to ensure respect for the regulations of legal metrology.

— to organise training in legal metrology

— to represent the country in international activities regarding legal metrology.

(*ix*) **National Service of Legal Metrology.** The National Service of Legal Metrology has following organisations to assist it in discharge of its duties :

— National Bureau of Legal Metrology. (It is the directing organisation)

— National Institute of Legal Metrology. (It is entrusted with the performance of scientific and research work)

— National Bureau of Verification.

There are Regional Bureau of Verification, Local Bureau of Verification, Mobile Bureau of Verification, and Verification Centres to assist National Bureau of Verification in ensuring appropriate accuracy of the standards, carrying out metrological supervision, verifying measuring instruments.

— Verification Agents (Authorised to exercise the functions of verification).

1.12. International System of Units (SI)

It is the system established in 1960 by the (CGPM) General Conference of Weights and Measures and abbreviated as SI (System International d'unites) in all languages. In India, we switched over to metric system of Weights and Measures conforming to SI units by an Act of Parliament No. 89, in 1956. This SI like traditional metric system, is based on decimal arithmetic. For each physical quantity, units of different sizes are formed by multiplying or dividing a single base value by powers of 10. Obviously this offers great advantage because the changes can be made very simply by adding zeros or shifting decimal point. In the metric system we have been following so far, this simplicity of a series of units linked by powers of 10 is limited to plain quantities like length, and this simplicity is lost when more complex units like energy etc. are encountered. For example energy is now represented by several units like kgm, H.P., kW etc. In contrast the SI provides only one basic unit for each physical quantity, and universality is thus achieved. This system in superior to other systems and also more convenient as it is coherent, rational and comprehensive.

The SI is a coherent system, in the sense that the product or quotient of any two unit quantities in the system is the unit of the resultant quantity, *e.g.* if unit of length is metre, then unit of area will be square metre and not acres or begas etc. It is rational system since it has absorbed in itself the rationalised MKSA system. It is also comprehensive because its seven base units cover all disciplines.

The seven base SI units established by the General Conference of Weights and Measures are given on next page and SI units having special names are given below.

SI UNITS HAVING SPECIAL NAMES

Physical quantity	*Name of unit*	*Unit symbol*
Force	newton	$N = kg\ m/s^2$
Work, energy, quantity of heat	joule	J = N m
Power	watt	W = J/s
Electric charge	coulomb	C = A.s
Electric potential	volt	V = W/A
Electric capacitance	farad	F = C/V
Electric resistance	ohm	Ω = V/A
Electric conductance	siemen	S = A/V
Magnetic flux	weber	Wb = V × s
Inductance	henry	H = V.s/A
Luminous flux	lumen	lm = cd.sr
Magnetic flux density	tesla	$T = Wb/m^2$
Illumination	lux	$lx = lm/m^2$
Frequency	hertz	Hz = cycles
Pressure	pascal	$Pa = N/m^2$

S. No.	*Physical Quantity*	*Name of unit*	*Unit symbol*	*Base of Definition*	*Definition*
1.	Length	metre	m	Wavelength of red light in Krypton 86	1,650,673.73 wavelengths in vacuo of the radiation corresponding to the transition between the energy levels $2p$ 10 and $5d5$ of the Krypton 86 atom.
2.	Time	second	s	Cycles of radiation of cesium	The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
3.	Mass	kilogram	kg	Platinum-cylinder prototype	Mass of the International prototype which is in the custody of Bureau International des Poids et Mesures (BIPM) at Sevres, near Paris.
4.	Temperature	kelvin	K	Absolute zero and water	The fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
5.	Electric current	ampere	A	Force between two conducting wires	The constant current which, if maintained in two parallel rectilinear conductors of infinite length, of negligible circular cross-section, and placed at a distance one metre apart in vacuum would produce between these conductors a force equal to 2×10^{-7} N/m length.
6.	Luminous intensity	candela	cd	Intensity of an area of platinum	The luminous intensity, in the perpendicular direction, of a surface of 1/600,000 square metre of a black body at the temperature of freezing platinum under a pressure of 101,325 newtons per square metre.
7.	Quantity of substance	mole	mol	Amount of atoms in carbon 12	The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

Other physical quantities are derived from these basic units. For example, volume is cubic metre (m^3), speed is metre per second (m/s), force is mass-metres per square second (kg m/sec^2). Realising that some derived units may be compex array of base units, some units have been given special names. They are given on page 24.

SI also recommends the use of supplementary units, the only authorised supplementary units being measures for plane and spherical angles. Though these could be expressed by base units but have been available as a convenience to users. Plane angles are represented by radians and solid angles by steradians.

Decimal multiples and sub-multiples of the SI units are formed by means of the prefixes given below, which represent the numerical factors shown :

Multiplication factor	*Prefix*	*SI Symbol*
10^{12}	tera	T
10^{9}	giga	G
16^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*To be avoided where possible.

The two major advantages of coherency of SI units are (*i*) same system and unit of measurement are used regardless of industry, trade, or discipline ; and (*ii*) minimum of conversion factors are needed (other than powers of 10).

In connection with SI units, some rules of style, abbreviations, writing, and drafting practices are applied, some of which are described below :

(*a*) No dots, commas, etc., are used after SI symbols except at the end of sentences. For example 32 metres will be written as 32 m but when written as 32 m. is not correct.

(*b*) Plurals are never used in connection with SI unit symbols, for example 32 metres will be written as 32 m and not as 32 ms which would mean 32 milli-seconds.

(*c*) Decimal fractions are always started with 0. For example, half metre will be written as 0.5 m and not as .5 m.

(*d*) Multiplication or times sign is '.' This is used between the number to be multiplied and between unit symbols in derived units where two unit symbols adjoin for the purpose of clarity, *e.g.* unit of torque may be written as m.N (metre newton) which if written as mN can be misunderstood as millinewton.

(*e*) All symbols and prefixes are lowercase letters, except symbols derived from proper names, like W for watt, M, G and T for the largest three power-of-10 prefixes. All symbols should be used as they are to avoid any confusion.

(*f*) All units may be written either in full or using the agreed symbols. There is only one acceptable symbol in all languages for a metric unit. For example KILOGRAM be written as kg and not as kgm or kg, or kgr. etc.

(*g*) The product of two or more units is preferably indicated by a dot which can be dispensed with when there is no risk of confusion with another unit symbol *e.g.*, 63 N.m or 63 Nm is correct but not 63 mN.

(*h*) There is a mixture of capital and lower case letters in the symbols for the prefixes, but the full names of the prefixes commence with lower case letters only, *e.g.* 200 MW is written is 200 megawatts.

(*i*) No degree mark (°) is used with kelvin, the unit of temperature. A temperature interval can also be expressed in degree celsius.

(*j*) Double prefixes should not be used *e.g.* one kilo Megawatt may not be written as kMW, but as GW.

(*k*) Algebraic symbols representing quantities are written in *italics* while symbols for units are written in upright characters.

(*l*) The expression "per" in symbols of derived units is always indicated by a fraction line as m/s of $\frac{m}{s}$ but word "per" or letter "p" should not be used for this purpose.

(*m*) Always leave one space between numerical value and the symbol. For example, 92 N is commitment 92N is not.

(*n*) Only the numerator should be multiplied by powers of 10 in compound derived units and the denominator should always remain the base unit.

For example 0.032 m/s may be put as 32 mm/s and not as 0.000032 m/ms. (meter per millisecond).

(*o*) Numbers may be grouped in clusters of three in both directions from the decimal mark, and gap may be given for clarity and comma should not be used there.

e.g. 153297.3 m may be written as 153 297.3 m and not 153,297.3 m. A sequence of four figures is generally not broken in groups.

(*p*) Units with names of scientists should be capitalised when written in full.

(*q*) According to SI recommendations, litre is a special name given to cubic decimetre and the world litre should not be used for expressing results of high precision volume measurements.

(*r*) Some units which though strictly incompatible with SI units, have been allowed initially, like km/hr, rev/min.

(*s*) The appropriate integers, multiples and sub-multiples to which a unit is to be expressed is selected in such a manner that the numerical value to be expressed is between 0.1 and 1000.

(*t*) Figures are written in groups of three to the left and to the right of the decimal sign.

(*u*) Thousands are separated by a space and NOT by a comma *e.g.* 6000 000 kl is correct but 6,000,000 kl is not correct.

(*v*) In some countries, a point (dot) is used as the decimal marker, and in some countries a comma is used ; both are understood internationally.

Question. Correct the mistakes in following numbers and symbols :

1. mps
2. $\frac{1}{32\text{nd}}$, 1/32nd
3. 45mm .5, 45.5mms, 45.5m/m
4. 4.96w
5. 2 $\frac{1}{2}$ Hrs, 14.30 hours
6. Km, kms
7. 19 M
8. M., ms
9. Sq.m.
10. C-m, M-W
11. cms, cm., cent
12. cc, cu^3, C
13. m/m, mms, millim

14. Kg, kgr, kgs, kilo
15. gr, Gr, grs, grm
16. H
17. 962N
18. min., mins.,
19. ″, sec., secs
20. KW (electric consumption)
21. kph, k.p.h., km.p.h.
22. 396 70, 39,670
23. m/s/s
24. 96253.5297
25. m.kg/s^2/J
26. 1 m μm
27. μ kg
28. 9.6×10^4 N
29. 1523 Pa
30. 0.00036 m
31. 7.8×10^{-8} s
32. 100 kgs.

Sol. The correct notations are as under :

1. $\frac{m}{s}$, m/s, ms^{-1}
2. 1 : 32 or 1/32 or $\frac{1}{32}$.
3. 45.5 mm
4. .96 W
5. 14 h 30 min or 14 hours 30 minutes
6. km or kilometre
7. 19 m
8. m or metre
9. m^2 or square metre
10. cm, MW
11. cm or centimetre
12. cm^3 or cubic centimetre
13. mm or millimetre
14. kg or kilogram
15. g or gram
16. h or hour
17. 962 N
18. min or minute (time)
19. s or second (time)
20. kWh or kilowatt-hour

21. km/h
22. 39 670
23. m/s^2, ms^{-2}
24. 96 253.529 7
25. $m.kg/(s^2J)$ or $m.kg\ s^{-2}\ J^{-1}$
26. 1 nm
27. mg
28. 96 kN
29. 1.523 kPa
30. 0.36 mm
31. 78 ns
32. 100 kg

1.13. Role of National Physical Laboratory (NPL) in Metrology

NPL provides the basic backbone of organizational structure for metrology in India. NPL is the custodian of national measurement standards for physical measurement in the country. This premier national laboratory is established with the objective to strengthen and advance physics-oriented research for the overall development of science and technology in the country. NPL has the responsibility of physical measurements based on the International system (SI units) under the subordinate legislation of Weights and Measures Act 1956 (reissued in 1988 under the 1976 Act). NPL also has the statutory obligation to establish, maintain and update the national standards of measurement and calibration facilities for different parameters. NPL maintains seven SI base units, *viz.*, meter, kilogram, second, kelvin, ampere, candela, mole (mol) and the SI supplementary units radian (rad) and steradians (sr).

The main objectives of the NPL's work are as follows :

— To establish, maintain and improve continuously the national standards for measurements for the benefit of the country and also to realize the units based on International Systems (SI),

— To determine the major physical constants,

— To develop and evaluate measurement techniques,

— To assist industries, governmental and other agencies in their developmental task by precision measurements, calibration and development of devices and processes related to physics,

— Laboratory's commitment to good professional practice and quality of its calibration and testing in serving to industry, and

— Technical advisory services, information, extension, consultancy and training and collaboration with universities and other organization.

Under the Standards of Weights and Measures Rules 1988, the NPL has been further assigned the obligation to act as the custodian of the national standards of measurement (excepting those for ionizing radiations) compatible and traceable to the International System (SI units). The NPL fulfils this responsibility by developing, maintaining and updating of these standards through interaction and metrological intercomparison with other major standards laboratories in the NPL (UK), NIST (USA), WNIFTRI (Russia), PTB (Germany), IMGC (Italy), BIPM (France), ETL (Japan), NIM (China), CSIR (Australia), DSIR (New Zealand), NRC (Canada) and, directory of National Measurement Systems of Non-Aligned (NAM) Countries and other Developing Countries.

The NPL represents India in the Bureau of International Weights and Measures (BIPM), General Conference on Weights and Measures (CGPM) and International Committee for Weights and Measures (CIPM) besides several other international committees in the area of acoustics and vibration, time and frequency, vacuum and pressure, temperature, humidity and other parameters also.

The nodal work done by the NPL in metrication of the entire measurement system of the Country since 1956 forms the basis of legal metrology function in the country coordinated by the Directorate of Weights and Measures (DWM) Govt. of India. Measurement standards, calibration service, specialized testing back-up, technical advisory consultancy services and participation in the committees of the DWM form the bulk of NPL support for these important areas of consumer scientific knowledge, protection and improvement and securing of the living conditions.

The principal activities of the NPL in the field of metrology include the development of :

— Physicso-mechanical standards : length standards and dimensional metrology, mass, volume and viscosity, fluid flow measurement, standards of force and hardness, pressure/vacuum, temperature, optical radiation, ultraviolet radiation, infrared radiation, acoustics and ultrasonic.

— Electrical standards : dc measurement, Josephson voltage, ac standards and standards of LF and HF impedance, magnetic standards, HF, MW voltage, current power, HF, MW attenuation and impedance standards.

— Other standards : Time and frequency, NABL programme, piezoelectric accelerometer, humidity standards.

— Calibration and Testing Service Programme,

— Reference material standards, and

— Participation in international metrology activities.

1.14. Sources of Errors

In any measurement, there is always a degree of uncertainty resulting from measurement error, *i.e.* all measurements are inaccurate to some extent Measurement error is the difference between the indicated and actual values of the measurand. The error could be expressed either as an absolute error or on a relative scale, most commonly as a percentage of full scale. It is important to examine fully the errors in measurement systems that cause these uncertainties, the meaning and interpretations of these errors and methods of reducing or circumventing of errors. Each component of the measuring system has sources of errors that can contribute to measurement error.

Instrument or indication errors may be caused by defects in manufacture of adjustment of an instrument, imperfections in design, etc.

The error of measurement is the combined effect of component errors due to various causes. There may be errors due to method of location, environmental errors, errors due to the properties of object of measurement, *viz.* form deviation, surface roughness, rigidity, change in size due to ageing etc., observation errors.

The total error of measurement includes indication errors, errors of gauge blocks or setting standards, temperature change errors, and errors caused by the measuring force of the instrument.

During measurement several types of errors may arise such as static errors, instrument loading errors or dynamic errors, and these errors can be broadly classified into two categories *viz.* controllable errors and random errors.

Static Errors. These result from the physical nature of the various components of the measuring system as that system responds to a fixed measurand input. Static errors result from the intrinsic imperfections or limitations in the hardware and apparatus compared to ideal instruments. The environmental effect and other external influences on the properties of the apparatus also contribute to static erros. Other sources of static errors could be inexactness in the calibration of the system, displaying the output of the measuring system in a way that requires subjective interpretation by an observer. From above it could be concluded that static errors stem from three basic sources : reading error, characteristic error and environmental error. In the measurement of length of a surface table with a rule, these errors will be encountered when aligning the ends of the rule and surface table, and when estimating the length of the table. The static error divided by the measurement range (difference between the upper and lower limits of measurement) gives the measurement precision. *Reading error* describes such factors as parallax, interpolation, optical resolution (readability or output resolution). Reading errors apply exclusively to the readout device and have no direct relationship with other types of errors within the measuring system. Attempts have been made to reduce or eliminate the reading errors by relatively simple techniques. Where there is possibility of error due to parallax, the use of mirror behind the readout pointer or indicator virtually eliminates occurrence of this type of error. *Interpolation error* can be tackled by increasing the optical resolution by using a magnifier over the scale in the vicinity of the pointer. The use of digital readout devices is increasing tremendously for display purposes as it eliminates most of the subjective reading errors usually made by the observer. However, there exists a possibility of plus or minus one count error in digital readout devices also and its value can be effectively reduced by arranging full range to correspond to huge number of pulses so that one pulse has very negligible value. Digital counting devices are capable of counting each and every pulse, however short may be the duration, but it is only during start and at stop that one pulse is likely to be missed which can lead to error.

Environmental errors result from effect of surrounding temperature, pressure and humidity on measuring system. It can be reduced by controlling the atmosphere according to estipulated requirements. External influences like magnetic or electric fields, nuclear radiation, vibration or shock, periodic or random motion etc., also lead to errors. It is important to note that these factors affect both the measuring system and measurand, and usually the effects of these factors on each component are independent. Thus the environmental errors of each component of the measuring system make a separate contribution to the static errors. Due to this reason, the number of environmental variables and external influences that could affect the measurement should be minimised and where it is not possible to do so then their effect should be computed and taken into account.

Characteristic error is defined as the deviation of the output of the measuring system under constant environmental conditions from the theoretically predicted performance, or from nominal performance specifications. If the theoretical output is a straight line, then linearity, hysteresis, repeatability, and resolution errors are part of the characteristic error. Linearity errors, hysteresis and repeatability errors are present to some degree in each component of a measuring system. Other characteristic errors include gain errors and zero offset, often collectively called calibration errors.

Similar characteristic errors in each component of the measuring system tend to be additive. Thus, system linearity is usually the sum of the errors in individual components ; and as such the study of combination and accumulation of errors is very important and will be discussed later.

It has been found that the static erros introduced by the components of the measuring system are the cause of major concern. However, the loading errors and dynamic errors which are generally encountered in process measurements and not in the field of Metrology, will also be discussed in brief here to complete the subject.

Loading errors result from the change in the measurand itself when it is being measured, *i.e.* after the measuring system or instrument is connected for measurement. Instrument loading error is thus the difference between the value of the measurand before and after the measurement system is measured. One example of such an error could be the deformation of soft component under contact pressure of measuring instrument. The effects of instrument loading are unavoidable and must be determined specifically for each measurement and measurand. Such loading erros are often the single greatest uncertainty in a physical measurement. Therefore, measuring system should be selected such that its sensing element will minimise instrument loading error in the particular measurement involved. In a steady state measurement, the cumulative effect of static errors and instrument loading errors determines the accuracy of the measurement.

Dynamic error is caused by time variations in the measurand and results from the inability of a measuring system to respond faithfully to a time-varying measurand. Usually the dynamic response is limited by inertia, damping, friction or other physical constraints in the sensing or readout or display system. Dynamic error is characterised by the frequency and phase response (Bode criterion) of the system for the cyclic or periodic variations in the measurand input. For random or transient inputs, the dynamic error is described by the time constant of response time. In both the cases , it is essential that dynamic characteristics of the measuring system be known before putting the system to measure time varying inputs.

It is thus seen that different errors entering into any observation arise due to a variety of reasons. Many times it may not be possible to identify the source of errors. Therefore it is more fruitful to classify errors according to the effects they produce rather than on the basis of sources which produce them.

For statistical study and the study of accumulation of errors, errors are categorised as controllable errors and random errors.

(*a*) **Systematic or Controllable Errors.** Systematic error is just a euphemism for experimental mistakes. These are controllable in both their *magnitude* and *sense*. These can be determined and reduced, if attempts are made to analyse them. However, they can not be revealed by repeated observations. These errors either have a constant value or a value changing according to a definite law. These can be due to :

1. *Calibration Errors.* The actual length of standards such as slip gauges and engraved scales will vary from nominal value by small amount. Sometimes the instrument inertia, hysteresis effect do not let the instrument translate with complete fidelity. Often signal transmission errors such as drop in voltage along the wires between the transducer and the electric meter occur. For high order accuracy these variations have positive significance and to minimise such variations calibration curves must be used.

2. *Ambient Conditions.* Variations in the ambient conditions from internationally agreed standard value of 20°C, barometric pressure 760 mm of mercury, and 10 mm of mercury vapour pressure, can give rise to errors in the measured size of the component. Temperature is by far the most significant of these ambient conditions and due correction is needed to obtain error free results.

3. *Stylus Pressure.* Error induced due to stylus pressure is also appreciable. Whenever any component is measured under a definite stylus pressure both the deformation of the workpiece surface and deflection of the workpiece shape will occur.

4. *Avoidable Errors.* These errors include the errors due to parallax and the effect of misalignment of the workpiece centre. Instrument location errors such as placing a thermometer in sunlight when attempting to measure air temperature also belong to this category.

5. Experimental arrangement being different from that assumed in theory.

6. Incorrect theory *i.e.*, the presence of effects not taken into account.

(*b*) **Random Errors.** These occur randomly and the specific cases of such errors cannot be determined, but likely sources of this type of errors are small variations in the position of setting standard and workpiece, slight displacement of lever joints in the measuring joints in measuring instrument, transient fluctuation in the friction in the measuring instrument, and operator errors in reading scale and pointer type displays or in reading engraved scale positions.

Characteristics of random errors

The various characteristics of random errors are :

— These are due to large number of unpredictable and fluctuating causes that can not be controlled by the experimenter. Hence they are sometimes positive and sometimes negative and of variable magnitude. Accordingly they get revealed by repeated observations.

— These are caused by friction and play in the instrument's linkages, estimation of reading by judging fractional part of a scale division, by errors in positioning the measured object, etc.

— These are variable in magnitude and sign and are introduced by the very process of observation itself.

— The frequency of the occurrence of random errors depends on the occurrence probability for different values of random errors.

— Random errors show up as various indication values within the specified limits of error in a series of measurements of a given dimension.

— The probability of occurrence is equal for positive and negative errors of the same absolute value since random errors follow normal frequency distribution.

— Random errors of larger absolute value are rather than those of smaller values.

— The arithmetic mean of random errors in a given series of measurements approaches zero as the number of measurements increases.

— For each method of measurement, random errors do not exceed a certain definite value. Errors exceeding this value are regarded as gross errors (errors which greatly distort the results and need to be ignored).

— The most reliable value of the size being sought in a series of measurements is the arithmetic mean of the results obtained.

— The main characteristic of random errors, which is used to determine the maximum measuring error, is the standard deviation.

— The maximum error for a given method of measurement is determined as three times the standard deviation.

— The maximum error determines the spread of possible random error values.

— The standard deviation and the maximum error determine the accuracy of a single measurement in a given series.

From the above, it is clear that systematic errors are those which are repeated consistently with repetition of the experiment, whereas *Random Errors* are those which are accidental and whose magnitude and sign cannot be predicted from knowledge of measuring system and conditions of measurement.

Spurious errors and Dixon test. Errors due to operator mistakes or malfunction of instrument are called spurious errors and need to be ignored in the statistical analysis. Statistical outlier or Dixon test is applied to discard spurious readings. All good observations follow normal distribution and spurious reading will fall outside the normal distribution. In Dixon test, all observations are arranged in ascending order if spurious reading is suspected for high value, or descending order if spurious reading is suspected for low value.

If total readings upto suspected value X_n are n, then value of $\frac{X_n - X_{n-1}}{X_n - X_1}$ is calculated for n between 3 and 7, $\frac{X_n - X_{n-1}}{X_n - X_2}$ for n between 8 and 10, $\frac{X_n - X_{n-2}}{X_n - X_2}$ for n between 11 and 13, and

$\dfrac{X_n - X_{n-3}}{X_n - X_3}$ for n between 14 and 24. If this ratio is more than following critical value, then X_n should be discarded :

n	*Critical value*	n	*Critical value*	n	*Critical value*
3	0.941	11	0.576	19	0.462
4	0.765	12	0.546	20	0.450
5	0.620	13	0.571	21	0.440
6	0.560	14	0.546	22	0.430
7	0.507	15	0.525	23	0.421
8	0.554	16	0.507	24	0.413
9	0.512	17	0.490	25	0.406
10	0.477	18	0.475		

Statistical Treatment of Errors. Random and systematic errors are evaluated and studied by statistical procedures which make it possible to state from a limited group of data the most probable value of a quantity, the probable uncertainty of a single observation, and the probable limits of uncertainty of the best value that can be derived from the data. It may be noted that the object of the statistical methods ; based on laws of chance which operate only on random errors and not on systematic errors ; is to achieve consistency (precision) of value and not their accuracy (approach to the truth).

It is also important to note that in quality control of a product we must consider variations in the repeat measurement of a single part as well the variations in the single measurements of a large number of 'so-called' identical parts. The first is largely due to error in the instrument whereas in the second there is also a contribution caused by variations as a result of the manufacturing process. The first is the study of errors (dealt here) and the second is the subject of statistical quality control (dealt in chapter 18).

Let us first understand some terms used in statistical analysis as under :

Population of Measurement. An infinite number of independent measurements carried out for determination of a certain quantity constitute a population.

Sample of Measurements. In practice, only a finite number of measurements are carried out for determination of a certain quantity which constitute a sample.

Sample Mean. If $x_1, x_2, x_3, \ldots x_n$ be n measurements then sample mean $\bar{x}$ is

$$= \sum_{i=1}^{n} (x_i/n) = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i$$

Sample Standard Deviation. Sample standard deviation 's' is defined as

$$s = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2/n}$$

Variance of sample $= s^2 = \dfrac{1}{n} \cdot \displaystyle\sum_{i=1}^{n} (x_i - \bar{x})^2.$

Population Mean. The limiting value of sample mean as number of measurements tends to infinity is called population mean

$$\mu = \lim_{n \to \infty} \sum_{i=1}^{n} (x_i/n)$$

Population Standard Deviation. The limiting value of sample standard deviation as number of measurements tends to infinity is called population standard deviation

$$\sigma = \lim_{n \to \infty} \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 / n}$$

Estimate of Population Standard Deviation. An estimate S of the population standard deviation is obtained from sample standard deviation as

$S = s\sqrt{n/(n-1)}$, where s = sample standard deviation.

Random Uncertainty (Ur).

$$U_r = t \,.\, S/\sqrt{n} = t.\frac{s}{\sqrt{n-1}}$$

where t is Student's 't' factor and $S/\sqrt{n}$ is the standard error of the mean, assuming that measurements follow the Gaussian (Normal) distribution.

Systematic Uncertainty (US)

Contributions due to measuring instruments, operating conditions and inherent characteristics of the instrument are taken into consideration.

Uncertainty reported in the certificates of calibration for measurement standards and instruments normally follow Rectangular Distribution with semi-range α. Then variance may be taken a $\alpha^2/3$. Systematic uncertainty $Us = K\,\sigma_s$.

K is the value of student 't' for $n = \infty$ at the desired confidence level and value of $K = 0.675$ for CL of 50%, 1.00 for CL of 68.3%, 1.96 for CL of 95%, 2.58 for CL of 99% and 3.0 for CL of 99.7%.

Overall Uncertainty U

There is no universal agreement for combining the systematic and random uncertainties. One view is to add the two, another is to use the quadrature method while third is to report them separately.

Principles of Least Squares. Assessment of deviation of errors relative to some particular datum may be done with the help of the principle of least squares. The principle states that the most probable value of observed quantities is that which renders the sum of the squares of residual errors a minimum.

Let a number of repeated readings on a component be represented by $x_1, x_2, x_3, \ldots\ldots x_n$. It can now be shown by least squares principle that the most probable value of the series of observed results is the arithmetic mean $\Sigma x/n$ as follows :

Let the most probable value be assumed to be x'. Then the deviation of any particular value x from the most probable value x' is $(x - x')$. From the least square principle $\Sigma(x - x')^2$ should be minimum, *i.e.*.

$$\frac{d\Sigma(x - x')^2}{dx'} = -2\,\Sigma\,(x - x') = 0$$

Therefore, $\Sigma x - nx' = 0$ or $x' = \dfrac{\Sigma x}{n}$ = arithmetic mean.

Error distribution. Virtually all instrument errors are random in nature. Exceptions to these, such as non-linearity errors and other errors are called systematic errors.

Random errors have positive and negative values and their magnitudes are generallv distributed in accordance with the Gaussian Distribution—the familiar bell-shaped curve shown in Fig. 1.6.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}}\,e^{-x^2/2\sigma^2} \qquad \ldots(1.1)$$

$$P(x_1 < x < x_2) = \frac{1}{\sigma\sqrt{2\pi}} = \int_{x_1}^{x^2} e^{-x^2/2\sigma^2}\, dx \qquad ...(1.2)$$

where $P(x)$ = probability density, x = error value

$P(x_1 < x < x_2)$ = probability that x (error value) lies within the interval x_1, x_2.

The curve (Fig. 1.6) and its mathematical expression [equation (1.1)] represents the probability distribution of the random errors. Since an error within the limits $-\infty$ to $+\infty$ is certain to occur, the area under the curve is numerically 1 ; representing a probability of 1. The probability that the error value lies between x_1 and x_2, $P(x_1 < x < x_2)$ is simply the area under the curve between these two points [equation (1.2)]. On a frequency basis, the area under the curve between error values x_1 and x_2 represents the percentage of all errors lying between these two values.

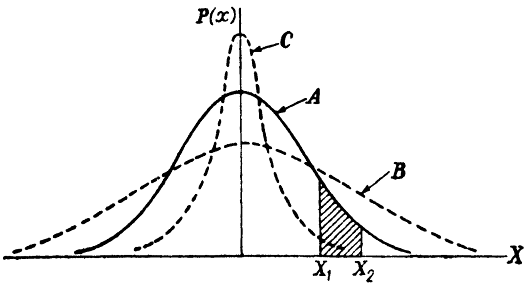


Fig. 1.6

Systematic errors are certain to occur and are, therefore, not treated statistically. If such errors are present in a system of random errors, they are simply added directly to the statistically combined random errors.

Errors Accumulation. The total static error of a measurement system can be measured in terms of root-mean-square (rms) of the component characteristic errors, if the following conditions are fulfilled :

Component characteristic errors are independent and of the same order of magnitude, and the distribution of errors is normal (Gaussian), *i.e.* we consider only the random errors ; and wherever possible this latter condition should be verified by experimental analysis.

The total static error of a measuring system, therefore,

$$= \sqrt{(LE_1 + LE_2 + ...) + RE^2 + CE^2 + EE_1^2 + EE_2^2 ......}$$

where LE = linearity errors of individual component ; RE = reading errors,

CE = characteristic errors (other than linearity) and EE = environmental errors.

Variance of Error Distribution

The basic measure of the random error distribution is the variance (σ^2) which indicates the spread or dispersion of the distribution function. Mathematically it is defined as :

$$\sigma^2 = \frac{1}{n} \sum_{i+1}^{n} x_i^2$$

where x_i = random error value and σ = standard deviation = RMS error.

If the variance is large, the error distribution curve (Fig. 1.6) is broad (curve B). Conversely, if the variance is small, the error distribution curve is quite narrow and peaked (curve C).

The square root of the variance or the "root mean square error" is also called the standard deviation (σ). It can be used to evaluate the most probable value of the measurement and is also quite useful in statistical analysis of Gaussian error distributions. For example, the mathematical nature of the Gaussian error distribution function is such that 68% of the errors represented by the distribution lie between the limits of $\pm$ 1σ, 94% between $\pm$ 2σ, and 99.7% between $\pm$ 3σ. Most of the instrument errors generally expressed are based on the 3σ limits. Thus, allowing for an error three times as great as the RMS static error gives a 99.7% probability that the measurement error is no greater.

1.15. Errors likely to Creep in Precision Measurements—Their Care

1.15.1. Effects of Environment—Temperature. Many applications specify tolerances in microns. It may be appreciated that 25 mm of steel will lengthen about 0.3 microns when its temperature is increased by 1°C. Obviously for precision measurements in terms of microns, error of 0.3 microns just by change of 1°C temperature is substantial. It should be understood that a piece of steel held in the hand absorbs heat very fast and upto 5°C rise in temperature can be expected in 5 minutes time, but it would take hours for it to cool to the laboratory temperature and obtain its original length. It would thus be realised that temperature has a great influence on accuracy of precision measurements. For such accuracy, it is essential that the gauge blocks and workpieces are handled with insulated forceps, or tweezers, with plastic pads or gloves. Usually a plastic shield is introduced in between the inspector and the machine so as not to influence temperature of machine surroundings due to presence by body radiant heat or hot breath or in any other way. In some interferometers, the machine is entirely enclosed in a box with transparent plastic and the operator manipulates the parts with long-handles, insulated forceps introduced through self-sealing rubber part holes. Prior to measurement, the parts, gauges and masters are all stored on the heat sink till they are stablised at the controlled room temperature. Heat sink consists of a slab of steel or aluminum of considerable mass with a clean-smooth surface.

To maintain such controlled temperature in air-conditioned gauging laboratory is essential. The cool air should be so deflected and diffused that the temperature in room will be same in any location but there should be no direct air currents to be noticed.

It may be mentioned that infra red rays from direct sunlight on the gauge would also tend to heat it even in air-conditioned room and, therefore, the sun rays should not enter the laboratory. Thus the stable atmospheric environment free from stray erratic temperature variations and soaking of gauges, masters and workpiece in heat sinks are essential for precise measurements. The temperature of the room should be measured precisely and recorded at regular intervals in the vicinity of gauges.

Internationally accepted temperature for measurement is 20°C and all instruments are calibrated at this temperature. In case workpieces and measuring instruments are of same material then there would be no need of maintaining temperature constant since both would expand equally. But different materials expand differently and hence the need of maintaining constant temperature.

Whenever gauges and workpieces have to be handled, as in the case of wringing of slip gauges, etc., these should be left on table for about an hour in order to enable them to attain uniform temperature of 20°C.

1.15.2. Effect of supports. In the case of long measuring bars, straight edges, these have been supported as a beam. The amount of their deflection due to supporting depends on the position of the supports. Slope and deflection at any point can be calculated by means of expressions derived from the theory of bending.

For a bar of length L, supported equidistant from the centre on supports by distance l apart, then for no slope at the ends, $l/L = 0.577$, and for minimum deflection of the beam, $l/L = 0.554$.

First condition is required for supporting standard bars and second condition is required in case of straight edges.

If a straight edge of rectangular section is quite true when laid on its side on a flat surface, it will not be straight when supported with its edge horizontal. The deflection is minimum when it is the same at the ends and the center. The necessary spacing of the supports is found by utilizing the mathematical relations for the bending of beam giving l/L equal to 0.554.

1.15.3. Effect of alignment. Abbe's principle of alignment should be followed in measurements to avoid cosine errors, sine errors, etc. According to this principle, the axis or line of measurement of the measured part should coincide with the measuring scale or the axis of measurement of the measuring instrument. Cosine error occurs in measuring the length of any part with a scale if the measuring scale is inclined to the true line of dimension being measured. In

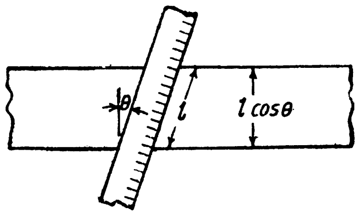


Fig. 1.7. (*a*) Cosine error.

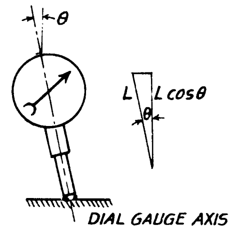


Fig. 1.7. (*b*) Errors due to non-alignment of plunger axis and line of measurement.

Fig. 1.7 (*a*) it may be seen that the length recorded is in excess of the true length by an amount $l(1-\cos\theta)$. However, this error is negligible in most cases since the angle θ is usually very small.

An alignment error of 2° over 1 metre introduces an error of approximately 0.6 mm.

Similarly error is introduced to dial indicator readings if the plunger axis does not coincide with the axis or line of measurement as in Fig. 1.7 (*b*).

If e = induced error and L = Change in indicator reading,
then $L \cos\theta$ = surface displacement and $e = L(1-\cos\theta)$.

To ensure correct displacement readings on the dial indicator, the plunger must, of course, be normal to the surface in both mutually perpendicular planes.

The measuring jaws of the vernier caliper are in effect extension of the scale markings on the instruments ; thus the jaws of an instrument in good condition are parallel and remain so at any measurement within the instrument range. The length l indicated on the scale corresponds to the displacement of the jaws from each other as in Fig. 1.8 (*a*). The effect of a bent scale beam is shown in Fig. 1.8 (*b*). The length l_1 between the extremes of the jaws has now become smaller than the length indicated on the scale. It is also evident that the error introduced is proportional to the length of the jaws and is at its minimum along the graduations line of the scale.

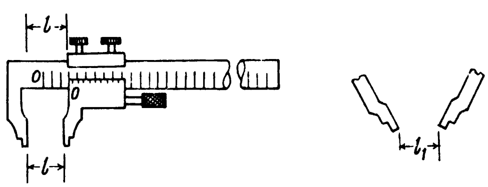


Fig. 1.8. Error introduced due to bent jaws of the vernier caliper.

Similar errors occur in the case of an indicator fitted with a ball-end stylus arm. In this case, it is important for the arm to be set so that the direction of movement of the work is tangential to the arc long which the ball moves. In both the cases of Fig. 1.9 (*a*) and (*b*), the reading on the indicator will be $h \sec\theta$, where h is the distance moved by the work. It may be remarked that some lever type test indicators are designed for use with their styli inclined at about 30° to the line of measurement and in these cases, an error would occur if it were set with the stylus normal to the line of measurement.

The combined sine and cosine errors occur when measuring an end gauge in the horizontal comparator if the gauge is so supported that its axis is not parallel to the axis of the measuring anvils, or if its each end, though parallel to each other, are not square to the axis.

With reference to Fig. 1.10

$$L = M\cos\theta - d\sin\theta$$

Errors of the above nature can be avoided by using gauges with spherical ends. It may be noted that

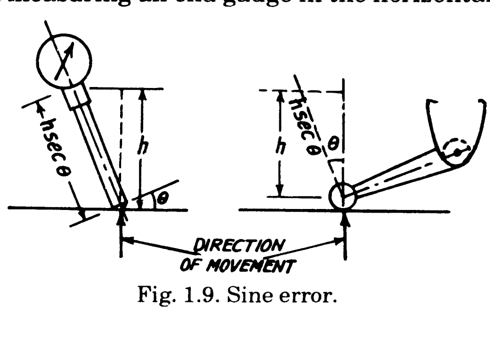


Fig. 1.9. Sine error.

such gauges need not be aligned accurately when used combination. Fig. 1.11 shows two gauges of this type with their axes out of line by an amount δ. The error in their combined length is very small, $(a + b)$.

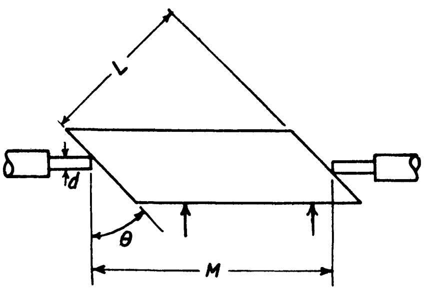


Fig. 1.10. Both sine and cosine errors.

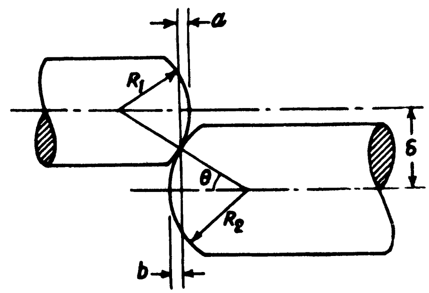


Fig. 1.11. Errors when spherical end gauges are not properly aligned.

$$a = R_1(1 - \cos\theta) = R_1\left(1 - \sqrt{1 - \sin^2\theta}\right)$$

$$R_1 = \left[1 - \sqrt{1 - \frac{\delta^2}{(R_1 + R_2)^2}}\right] = R_1\left[1 - \left(1 - \frac{\delta^2}{2(R_1 + R_2)^2}\right)\right] \text{ approx.}$$

$$= \frac{R_1\delta^2}{2(R_1 + R_2)^2}; \qquad \text{Similarly, } b = \frac{r_2\delta^2}{2(R_1 + R_2)^2}$$

Therefore,
$$(a + b) = -\frac{(R_1 + R_2)\delta^2}{2(R_1 + R_2)^2} = \frac{\delta^2}{2(R_1 + R_2)}$$

With 150 mm and 250 mm gauges out of line by 0.2 mm, the error in their combined length is only a tenth of micrometer. Longer gauges of course, result in a correspondingly smaller error, with standard special end pieces.

1.15.4. Dirt. Presence of dust in atmosphere may change reading by a fraction of micron. Where accuracy of the order of micron is desired, electrostatic precipitators need to be incorporated in the lab or in the air ducts in addition to air filters. Other sources of dust could be from clothing. The work-pieces and masters should, therefore, be cleaned by clean chamois or by a soft artists' brush. Dust inhibitors are also essential. The coated surfaces should be sprayed with a suitable filtered clean solvent. Gauges should never be touched with moist fingers.

1.15.5. Errors due to vibrations. For consistent and repetitive readings a gauge should be subjected to as little vibration as possible, or none. Vibrations can be eliminated by locating the lab properly away from vibration sources and slipping cork, felt or rubber pads under the gauge, and mounting the gauge pedestal or floor sections on tar mastic. Putting a gauge on a surface plate resting in turn on a heavy plate also reduces the effect of vibrations due to natural frequency of massive plate differing substantially from the immediate surroundings.

1.15.6. Metallurgical effects. The material for gauges should have been properly and naturally seasoned after heat treatment so that it attains stable dimensions ; otherwise measurement discrepancy may occur due to unstable, internal metallic structure.

The amount of surface roughness of gauge should be determined, because gauge almost invariably measures the peaks. The measurement may be disturbed by loosening up of tiny flakes of chrome on stainless steel. Tungsten carbides may have invisible pits which can influence readings.

Sometimes the size, area and weight of work-piece may create an error in obtaining a true dimension, for example, a 100 mm gauge block when tested in a horizontal position will give different readings than when placed vertically or suspended. Such errors would be noticeable on lengthy components above 450 mm in length.

1.15.7. Contact point penetration. Penetration is the bending, depressing, deforming and yielding of the surface of the workpiece under the pressure of the gauging contact. The penetration effect does occur and varies with the Young's modulus of the material being gauged. Tungsten carbide being rigid has nearly no penetration effect but brass yields readily. Penetration in the surface of a cylinder is found to be little greater than in a flat surface, which in turn is greater than in the bore of a ring.

For detecting size differences of less than 2-3 microns, gauging pressure is seldom trusted to human touch. Contact pressure in most precision gauges is controlled by spring action or by weights and counterweights. It may be appreciated that contact pressure (though it causes penetration errors) is essential in order to avoid any wavering of contact and ensuring certain contact. Vibration is the major cause of uncertain readings with light gauging pressure.

1.15.8. Errors due to deflection. Deflection of parts occurs due to contact gauging pressure. To avoid deflection errors, contact gauging pressure should be as small as possible, overhangs should be minimised, gauge frame should be made of rigid and adequate cross-section, and the gauge clamps or adjusting devices should be securely tightened. The deflection errors to some extent can be minimised by noting readings on comparator with master of same material as the workpiece. Sometimes free-rolling cylinders or balls are used under the work to avoid deflection errors by contact pressure. Jaws of precision calipers for internal diameter gauging are made of rigid material with cross-section areas great enough to reduce bending errors to negligible amounts.

In considering the total effect of stylus pressure, it is convenient to consider the two effects of deformation and deflection separately. The total error caused by the effect of stylus pressure may be obtained by adding the deformation and deflection values together. The deformation effect is shown in Fig. 1.12. The value of the deformation δ may be calculated from the relationship

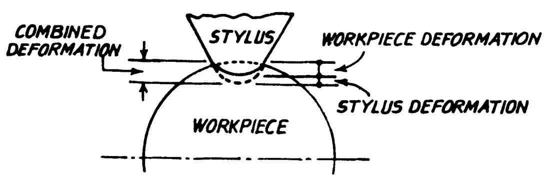


Fig. 1.12. Effect of contact pressure on measurement.

$$\delta = p^{2/3} B^{1/3} \lambda Y$$

where p = Stylus pressure, $B = \frac{1}{2R_1} + \frac{1}{2R_2}$

where R_1 = tip radius of stylus, R_2 = radius of workpiece

$$\lambda = \left(\frac{v_1 + v_2}{2} \right)^{2/3}$$

where v_1 = a constant dependent on the tip material

v_2 = a constant dependent upon the workpiece material

Y = a constant dependent upon the ratio of the geometry of the stylus to that of workpiece.

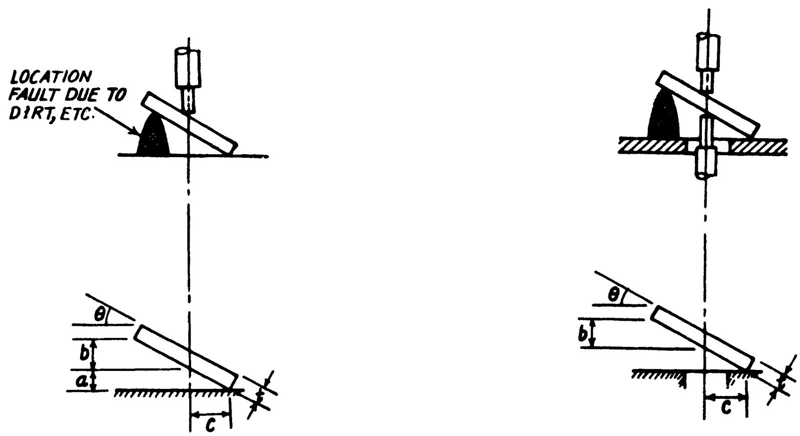
The deflection β of the hollow cylinder under the action of the stylus pressure has also been determined and may be calculated from the formula :

$$\beta = \frac{1.7856 R_m^2 p}{E L_e R_m t^3}$$

where p = stylus pressure, R_m = mean radius of workpiece, E = young's modulus of workpiece, L_e = effective length of workpiece, t = wall thickness of workpiece.

1.15.9. Errors due to looseness. Looseness leads to errors due to penetration and deflection. It results in inconsistent readings and inaccurate calibration. Looseness can be tested by setting the gauge contact on gauge anvil and zeroing the meter ; and then applying finger pressure or a light tab to each location, where looseness might be expected and noting the reading again. It is essential for this test that the gauge anvil should be clamped down securely to gauge frame. Metal chips or plain dirt between post and clamp can produce the pivoting effect. The gauge contact point should be tight in the spindle.

1.15.10. Errors due to wear in gauges. Wear on anvils and contacts is very troublesome. The internal instrument wear can also lead to measurement error, which can be checked by calibration. The extent of wear hollows in anvils and lack of parallelism can be readily measured with optical flats. The spherical contact can be checked by examination with a microscope. Wear can be minimised by keeping gauges, masters and workpieces clean and away from dirt. Carbide masters though wear resistant themselves, wear out hardened steel anvils. Cast-iron workpieces present the problem of sand particles. Gauge anvil and contact materials should be properly hardened. Chrome-plated parts have been found to withstand ten times more wear than unplated parts.



(*a*) Surface displacement
Reading = $a + b = c \tan\theta + t \sec\theta$
Error = $a + b - t = c \tan\theta + t(\sec\theta - 1)$

(*b*) Differential length measurement
Reading = b
Error = $b - t = t(\sec\theta - 1)$

Fig. 1.13. Errors due to faulty location.

1.15.11. Error due to location. Fig. 1.13 shows how imperfect location of surface causes errors and how differential measurement can reduce such errors.

1.15.12. The Parallax Effect. On most dials the indicating finger or pointer lies in a plane parallel to the scale but displaced a small distance away to allow free movement of the pointer. It is then essential to observe the pointer along a line normal to the scale, otherwise a reading error will occur. This effect is shown in Fig. 1.14, where a dial is shown observed from three positions

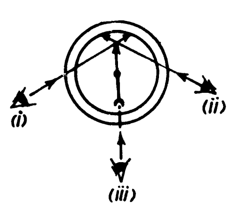


Fig. 1.14. Error due to parallax.

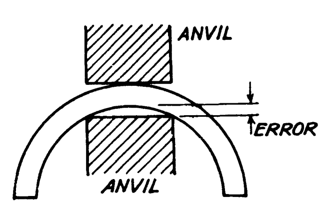


Fig. 1.15. Error due to poor contact.

where the pointer is set at zero on the scale. Observed from position (*i*) *i.e.* from the left, the pointer appears to indicate some value to the right of zero, and from position (*ii*) some value slightly to the left of zero, while only at position (*iii*) with the pointer coincide with zero on the scale. Rulers and micrometer thimbles are levelled to reduce this effect and on dials the indicators may be arranged to lie in the same plane as the scale thus completely eliminating parallax, or a silvered reflector may be incorporated on the scale so that the line between the eye and pointer is normal to the scale only when the pointer obscures its own image in the reflector.

1.15.13. Errors due to poor contact. Fig. 1.15 shows how the poor contact of working gauge or instrument with the workpiece causes an error. It would be appreciated that the gauge with wide areas of contact should not be used on parts with irregular or curved surfaces.

1.15.14. Error due to impression of measuring stylus. Every gauge stylus has relatively high weight. Fig. 1.16 shows how the impression of the gauge stylus indents the surface. Even a well supported, flat bar may be difficult to measure when the gauge indents the surface on contact. Optical or pneumatic instruments are best to avoid such error.

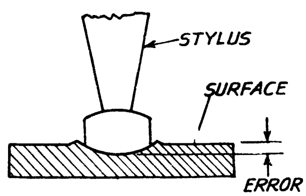


Fig. 1.16. Error due to impression of stylus on workpiece.

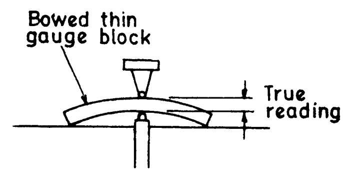


Fig. 1.17

Similarly distortions due to stylus pressure occur while measuring thin walled surface. Spring loaded gauges should be avoided and electronic/air gauges are best suited for such applications.

1.15.15. Importance of gauging set up to be square. Perpendicularity in gauging set ups should be ensured properly in precision measurements as an angular error of one minute in setting can cause 1 micron error in 100 mm. A comparator of gauge should be carefully checked for squareness from several different angles with the gauge clamped tight. Errors of perpendicularity may arise either due to gauge head not being set up perpendicular to workpiece or the reference anvil on which workpiece is placed may itself be tilted.

1.15.16. Gauging thin blocks. For gauging thin blocks, it is advisable to use dual gauging contact since these are liable to warp when not wrung together. Obviously enough if reading is taken with single gauging head with bowed thin gauge block placed on surface plate, the reading obtained will be much different, but two point gauging eliminates such problems.

1.16. Linearity

The output of a measuring system may be linear or non-linear. As long as the output is repeatable, it can always be calibrated, but for a non-linear system the construction of calibration curve becomes tedious, cumbersome and time-consuming. For a liner system, a simple two or three point calibration is sufficient and recalibration is also facilitated. Thus, a high degree of linearity, or the minimising of linearity error is very important characteristic of any measuring system. The more linear the measuring system is, the more readily it can be calibrated and the less uncertainty there will be about a particular output value indicated by the system.

As already indicated, characteristic error is defined as deviation of the output of a measuring system from the predicted performance, or from nominal performance specifications, under the condition of constant environment. According to this definition, the "theoretically predicted performance" or "nominal performance specification" is the norm of reference to which deviations are compared, and the basis of selecting a particular norm, particularly for linearity, is sometimes misunderstood. Linearity can be defined as the maximum deviation of the output of the measuring system from a specified straight line applied to a plot of data points on curve of measured values *versus* the measurand input value. As several lines can be used as linearity references, it becomes essential to clearly define the exact nature of reference straight line before interpreting or comparing the linearity specifications for a measuring system. The most common reference lines are :

(*i*) *Terminal line*—It is drawn from the origin to the data point at full scale output.

(*ii*) *End point line*—It is drawn between the end points of the data plot, usually without regard to the origin if the output is bipolar.

(*iii*) *Best fit line*—It is the line midway between the two closest parallel straight lines that enclose all the data points.

(*iv*) *Least square line*—It is the line for which the sum of the squares of the deviations of the data points from the line or curve being fit is minimised. This is the most favoured line and is truly best-fit curve in the sense that it comes as close as possible to each data point on a plot of output *versus* measurand input according to the least-square error criterion, *i.e.* to minimise the sum of the squares of the deviations of the data points from the curve being fit.

The least-squares line for a measuring system can be found from the established slope equations.

The slope m of the least square best-fit straight line for a collection of data points is given by :

$$m = \frac{\overline{x_i}\,\overline{y_i}}{\overline{x_i}^2} = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^2}$$

where x_i = input of measurand
y_i = output value (measured value)
n = No. of test data points.

Once the slope m is determined, it is possible to check the maximum deviation of linearity from the least squares line by the following relation :

$$\%\ \text{linearity} = \frac{y_{i\,max} - mx_i}{mx_{full\ range}} \times 100\%$$

where $y_{i\,max}$ = output value at point of maximum deviation from best-fit straight line
mx_i = point on best-fit straight line corresponding to maximum deviation point.

1.16.1. Application of the Least Squares Principle. The least squares principle has wide application in metrology for assessing the deviation of errors relative to some particular datum. In general the least squares principle states that the most probable value of observed quantities is that which renders the sum of the squares of residual errors a minimum.

1. *Series of Observed Values.* This situation occurs when a large number of readings are taken on the same dimension of a component.

Let the observed values be given by x_1, x_2, x_3 ... x_n. It can be shown by the least squares principle that the most probable value of the series of observed results is the arithmetic mean $\Sigma x/n$ as follows :

Let the most probable value be assumed to be X. Then the deviation of any particular observed value x from the most probable value X is $(x - X)$. From the least squares principle $\Sigma (x - X)^2$ should be a minimum, *i.e.*,

$$\frac{d\Sigma(x-X)^2}{dx} = 2\Sigma\,(x-X) = 0$$

$$\therefore \quad \Sigma x - nX = 0$$

$$X = \frac{\Sigma x}{n} = \text{arithmetic mean.}$$

2. *Series of Observed Values of Two Dependent Variables.* Such a problem arises in the measurement of straight edge when the variations (y) from a truly straight line are determined at a number of positions (x) along the straight edge.

Let the observed values be given by (x_1, y_1), (x_2, y_2) ...... (x_n, y_n).

The equation of the straight line is given by $X = ax + b$, where a is constant representing the slope of the line and b is constant representing the intercept on the y-axis. Referring to Fig. 1.18, let AB be any arbitrary straight line placed in relation to the observed points (x_1, y_1), (x_2, y_2), ... (x_n, y_n). Using this line to predict the value of y_1 from x_1, we get point P. Thus the difference of predicted value and the actual value will, therefore, be $y_1 - (ax_1 + b)$. What is required is to choose the best-fitting line with respect to the observed values by the method of least squares. This is done by choosing a line for which the sum of the squares of the deviations from it measured vertically is a minimum.

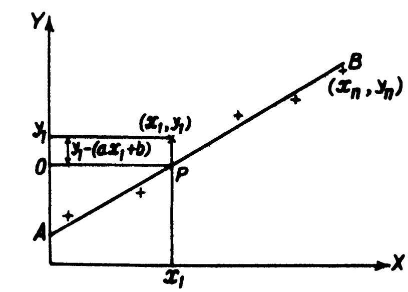


Fig. 1.18. Deviation of least-square line for two dependent variables.

Taking point (x_1, y_1), the square of the deviation of this point from the line is $[y_1 - (ax_1 + b)]^2$ and the sum of the squares of the deviation for all the points is given by :

$$E = \Sigma[y - (ax + b)]^2.$$

It is thus necessary to choose a and b to make E a minimum. This may be done by differentiating expression partially with respect to a and b and then equating each derivative to zero. Thus

$$\frac{dE}{da} = -2\,\Sigma x\,[y - (ax + b)] = 0 \qquad ...(1)$$

$$\frac{dE}{db} = -2\,\Sigma\,[y - (ax + b)] = 0 \qquad ...(2)$$

Equation (2) may be rearranged as follows :

$$\Sigma y = a\,\Sigma x + nb$$

$$\therefore \quad b = \frac{\Sigma y}{n} - \frac{a\Sigma x}{n} = \bar{y} - a\bar{x} \qquad ...(3)$$

where $\bar{y}$ = mean of $y_1, y_2, ..., y_n$ and $\bar{x}$ = mean of $x_1, x_2 ......, x_n$.

If these mean values are substituted in the expression $y = ax + b$ we obtain Eq. (3). The least squares line therefore passes through the mean of the points (x_1, y_1), (x_2, y_2), ..., (y_n, y_n).

Rearranging Eq. (1), we get $\Sigma xy = a\,\Sigma x^2 + b\,\Sigma x$

Substituting $b = \bar{y} - a\bar{x}$ in the above gives $a = \dfrac{(\Sigma xy - n\overline{xy})}{(\Sigma x^2 - n\bar{x}^2)}$ ...(4)

If the origin of the straight line is taken through the mean point $\bar{x}, \bar{y}$ the Eq. (4) reduces to :

$$a = \frac{\Sigma x_m\, y_m}{\Sigma x_m^2}$$

where x_m = reading in x-axis relative to $\bar{x}$, *i.e.* $x - \bar{x}$
and y_m = reading in y-axis relative to $\bar{y}$, *i.e.* $y - \bar{y}$.

3. *Series of Observed Values of Three Dependent Variables.* Such a problem arises in the measurement of a surface table when the variations (z) from a truly flat plane are determined at a number of positions (x, y) on the surface plane.

Let the observed values be given by (x_1, y_1, z_1), (x_2, y_2, z_2), ..., (x_n, y_n, z_n).

The equation of the flat plane is given by :

$$Z = ax + by + c.$$

Let any arbitrary plane be placed in relation to be observed points (x_1, y_1, z_1), (x_2, y_2, z_2) ......, (x_n, y_n, z_n). Using this plane to predict the value of z_1 from (x_1, y_1), we get a point N. Thus the predicted value of $z_1 = Z_1 = ax_1 + by_1 + c$. The difference between the predicted value and the actual value will therefore be :

$$z_1 - (ax_1 + by_1 + c).$$

What is required is to choose the best-fitting plane with respect to the observed values by the method of least squares. This is done by choosing a plane for which the sum of the squares of the deviations from it measured vertically is a minimum.

Taking point (x_1, y_1, z_1), the square of the deviation of this point from the plane is $[z_1 - (ax_1 + by_1 + c)]^2$ and the sum of the squares of deviation for all the points is given by

$$E = \Sigma\,[z - (ax + by + c)]^2.$$

It is thus necessary to choose a, b and c to make E a minimum. This may be done by differentiating the expression for E, partially with respect to a, b and c and then equating each derivative to zero.

Thus
$$\frac{dE}{da} = 2\Sigma x\,[z - (ax + by + c)] = 0 \quad ...(5)$$

$$\frac{dE}{db} = 2\Sigma y\,[z - (ax + by + c)] = 0 \quad ...(6)$$

$$\frac{dE}{dc} = 2\Sigma z\,[z - (ax + by + c)] = 0 \quad ...(7)$$

Eqn. (7) may be rearranged as follows :

$$\Sigma z = a\,\Sigma x + b\,\Sigma y + nc$$

$$\therefore \quad c = \frac{\Sigma z}{n} - \frac{a\Sigma x}{n} - \frac{b\Sigma y}{n} = \bar{z} - a\bar{x} - b\bar{y} \quad ...(8)$$

where $\bar{x}$ = mean of $x_1, x_2, ..., x_n$; $\bar{y}$ = mean of $y_1, y_2, ..., y_n$ and $\bar{z}$ = mean of $z_1, z_2 ......, z_n$.

If these mean values are substituted in the expression $Z = ax + by + c$ we obtain desired equation of plane. The least squares plane therefore passes through the mean of the points (x_1, y_1, z_1), (x_2, y_2, z_2), ..., (x_n, y_n, z_n). Eqns. (5) and (6) can now be rewritten as

$$\Sigma\, x = a\Sigma x^2 + b\Sigma xy + c\Sigma x \quad ...(9)$$

$$\Sigma yz = a\Sigma xy + b\Sigma y^2 + c\Sigma y \quad ...(10)$$

If the origin of the mean plane is taken through the mean point $\bar{x}, \bar{y}, \bar{z}$ then we may eliminate term c in expressions (9) and (10) and solve for a and b to give :

$$a = \frac{\Sigma y_m^2\, \Sigma x_m z_m - \Sigma x_m y_m\, \Sigma y_m z_m}{\Sigma x_m^2\, \Sigma y_m^2 - (\Sigma x_m y_m)^2}$$

$$b = \frac{\Sigma x_m^2\, \Sigma y_m z_m - \Sigma x_m x_m y_m\, \Sigma z_m}{\Sigma z_m^2\, \Sigma y_m^2 - (\Sigma x_m y_m)^2}$$

where x_m = readings in x-axis relative to $\bar{x}$, *i.e.*, $x - \bar{x}$
y_m = readings in y-axis relative to $\bar{y}$, *i.e.*, $y - \bar{y}$
z_m = reading in z-axis relative to $\bar{z}$, *i.e.*, $z - \bar{z}$.

1.17. Rigorous definitions of accuracy and precision. Say it is required to measure a dimension L. With highly accurate machine, we take several measurements and obtain a distribution (normal centred around mean ; strictly speaking, it is t-distribution which can be approximated with a normal distribution when the sample size or number of measurements is about 30 or greater). The difference δ between mean value and nominal dimension is called bias. Smaller the bias, the higher is the accuracy. Precision is measured as to how small is the dispersion ε from the mean value.

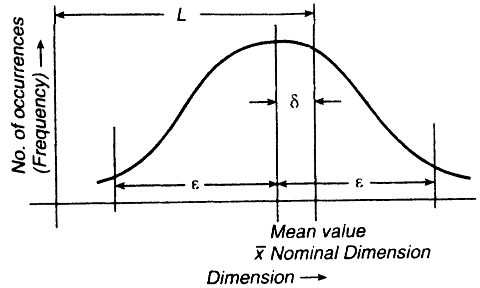


Fig. 1.19

When a bias exists, conditions are adjusted to compensate for δ to make $\bar{x}$ agree with L. Since compensation is done using sample mean $\bar{x}$ and not the population mean μ, there will be a slight error, and the corrected sample mean will still differ from L. The probabilistic range over which the difference $\delta = L - \bar{x}$ will be dispersed can then be used as a quantitative measure of accuracy and given as follows

$$\delta = t\left(\phi, \frac{\alpha}{2}\right)\lambda\sqrt{\frac{v}{n}}$$

where t (ϕ, $\alpha/2$) is the t-distribution value when the degree of freedom is $\phi = n - 1$
$1 - \alpha$ is the probability and can be determined from a mathematical table
n is sample size
α is the significance level

v is the unbiased variance defined as $v = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$

If $1 - \alpha$ is taken as 0.95 (*i.e.* 95% probability), n = 21, $N = 4\ \mu m^2$, then
t (20,0.05/2) = 2.09 (from a table)

and $$\delta = \text{accuracy} = 2.09 \times \sqrt{\frac{4}{21}} = 0.912\ \mu\text{m}$$

Thus accuracy of such a process is 0.912 μm with 95% reliability ; *i.e.* $\mu - \bar{x}$ will be within ± 0.912 μm with a 0.95 probability. This can also be expressed as 60.912 μm (95%).

Precision $$\varepsilon = t\left(\phi, \frac{\alpha}{2}\right)\sqrt{v} = 2.09 \times \sqrt{4} = 4.18\ \mu\text{m}$$

This is expressed as '4.18 μm (95%)'.

It means that the finished dimension will be dispersed within ± 4.18 μm of mean value with a probability of 0.95.

Accuracy and precision can be combined to give a broader definition of precision *i.e.* error limit $\tau = \delta + \varepsilon$.

If accuracy and precision can be estimated with sufficient reliability, then precision, broadly defined, can be obtained from the variance of dispersion of δ and ε, *i.e.* $\tau = \sqrt{\delta^2 + \varepsilon^2}$

1.18. Principles of High-precision Measurements

(*i*) Temperature of measurements needs to be clearly defined. An object placed at 21°C may take more than 10 hours to attain room temperature of 20°C. This is so because temperature decreases exponentially. The process can be quickened by placing the object on a large mass (say, surface place which acts as a heat sink). Since heat also flows by radiation, careful attention must be paid to prevent radiation due to lighting, sunlight, human bodies, and electric equipment from affecting measurements.

If object's temperature is at different temperature, then it must be monitored at all times, and measurement must be corrected for difference between object's temperature and reference temperature by calculation.

(*ii*) Measurement force should be avoided (non-contact methods of measurement be preferred).

(*iii*) The precision of the measuring instrument must be five to ten times higher than the expected precision of the measured object.

(*iv*) Be aware of the instrument's characteristics like undirectional approach to avoid backlash effects, completing measurements quickly to avoid drift etc.

(*v*) Influence of work-affected layers on surface. The surface layer affected by machining needs closer look for precision measurements. The presence of an affected layer will influence residual stress (cause of changes with age), surface processability, reflectance, electrical conductivity, corrosion resistance, and abrasion resistance.

Work affected layer must consist of four or five layers as follows : Around 1 μm thick outermost layer consisting of a nearly amorphous structure, followed by 10 μm fibrous layer which has undergone severe plastic deformation and which resembles rolled steel in grain structure. Below that is the plastically deformed layer consisting of crushed grains. Then comes the transgranular slippage layer, in which the grains still retain their form but some internal slippage exists. Depth of affected layer can be measured by :

(*i*) Ultrasonic microscope method, (*ii*) Corrosion method, (*iii*) microscopic analysis, (*iv*) X-ray diffraction method, (*v*) hardness method, and (*vi*) recrystallisation method.

1.19. Why Precision Measurements are required and Why Struggle for ever increasing Accuracy ?

The need for reliable data was recognised very early in the developmental science. Fig. 1.20 shows how the experiments have helped in establishing of theoretical postulates, and the experiments were possible only with the developments in precision measurements. The logical consequences of preconceived views could be demonstrated by carrying out experiments. Thus precision measurements form the background of advanced technology engineering.

Advancements in Reference Standards

Quantitative measurements require some sort of stable measurement standard if the results of measurements in different places and at different times are to be usefully compared. Intimately connected with the definition of units of measurements is the practical task of the physical realization of these units, since a paper definition serves no useful purpose if it cannot be realized with the required precision.

It was only since science reached the state where engineering began to rely on any significant extent upon the discoveries of physics, that accurate standards of measurement became necessary. Towards the middle of the nineteenth century the need for word-wide agreement on the principal units of measurement was felt and this led to the signing in 1875 of the Convention. The founding of the major national metrological laboratories took place soon after. In 1875 the only standards deposited were those of mass and length. The latter very quickly required the establishment of

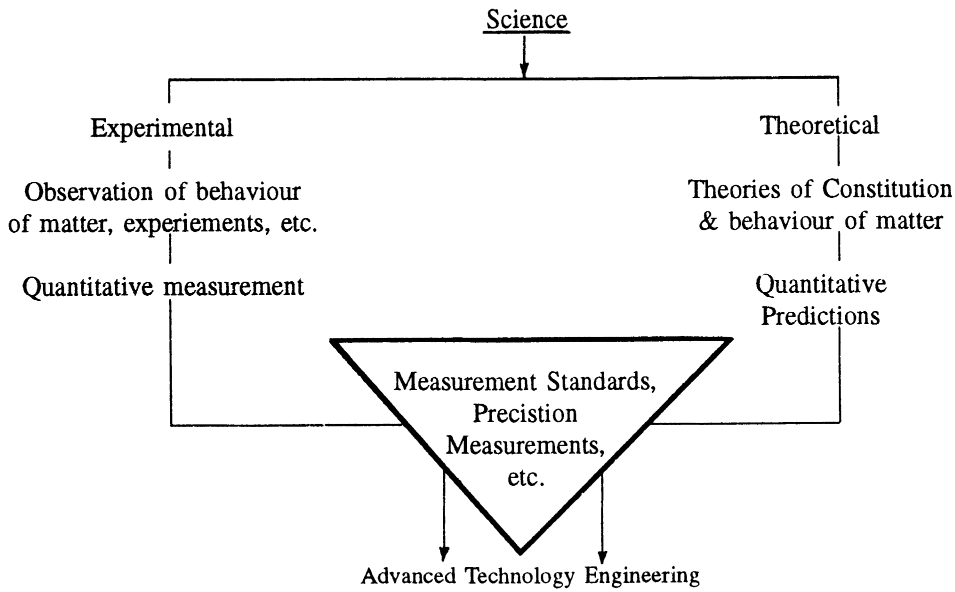


Fig. 1.20. The background of Advanced Technology Engineering.

accurate standards of temperature, since thermometers were needed to measure the thermal expansion of the meter bars.

During the second half of the nineteenth century some of the leading physicists devoted considerable time and effort to the problem of accurate measurement and the establishment of a consistent system of units. James Clerk Maxwell in 1870 stated, : "If we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions or the motion of the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable unalterable, and perfectly similar molecules." Indeed, as physics progressed it became possible to envisage practical units based upon atomic phenomena.

The establishment of useful units based upon atomic and, in due course, quantum phenomena, has not turned out to be easy. In order to establish an atomic or quantum-based base unit at least three conditions must be satisfied. First, one requires a good theoretical understanding of the quantitative behaviour of the atomic or quantum phenomenon in question and, second, a practical way of realizing the phenomenon must exist that allows an explicit theoretical description to be written down of the process employed, and third, a method is required of making a sufficiently accurate link between the other base units and the proposed atomic or quantum-based unit. It is often the third of these that turns out to be the most difficult. Nevertheless, it is in the attempt to use the fundamental physical constants as the bases of measurement standards that the role of precise measurement in physics became evident. In order to check that we have an adequate theoretical understanding of atomic or quantum phenomena we need to be able to check quantitative predictions made by theory. This can sometimes require the most accurate and precise measurements possible, to distinguish between competing theories or interpretations of theory.

The bases of measurement standards, the fundamental physical constants are useful only in so far as physical phenomena exist that can be described explicitly in terms of the fundamental constants, and which can at the same time, be measured in terms of the macroscopic base units. The extent to which this can be done is an indication of the extent to which modern atomic and quantum physics can be used to produce much of today's advanced technology. The practical application of atomic and quantum physics depends upon our ability to make the precise measurements that link these microscopic phenomena to the macroscopic world. An essential part of this is the accurate measurement of the fundamental physical constants in terms of the base units.

Quantum Physics and Precision Measurements

Almost all high accurate measurements are dependent upon quantum mechanical properties of system. Further there is no fundamental principle that forbids accurate classical measurements.

The application of advanced technology to classical measurements can lead to significant improvements in accuracy. The gas constant, which together with the gravitational constant has in the past always lagged far behind the other physical constants in the accuracy with which it is known, has recently been measured using a spherical acoustic resonator with an accuracy approaching 1 part in 10^6, and still further improvements seem possible. Some weighings are carried out as part of an experiment designed to search for a fifth force, that have exhibited standard deviations of about 5 parts in 10^{12} for series of measurements lasting a few days.

Such measurements outside the very limited immediate field of application are of interest because one finds that when an atomic or quantum phenomenon is used as the basis of a particular technology, there appears a demand for all aspects of that technology to increase in precision.

1.19.1. Nanometrology. In order to connect monomode optical fibres together it is necessary to have mechanical connectors that can mate with axial errors of fractions of a micrometer. Such dimensional tolerances are characteristic of the demands now being placed upon length or dimension metrology by the optoelectronics industries.

The increase in the density of packing of circuit elements on silicon wafers has resulted in the dimensions of individual elements falling to tens of nanometers. In order to make such devices it is now necessary to be able to identity and reproduce the position that objects should have on a silicon wafer to this accuracy. Thus on a part of a silicon wafer roughly 10 cm square it is necessary to be able to locate and identify any point with a precision of 10 or 12 nm. The requirement in any particular production line may indeed be only for relative precision, but as soon as the process is transferred elsewhere, either to another factory or even to another part of the same factory, the position of a point on the wafer must be expressed in some unit. While in the short term a wholly local unit can be maintained, based upon the properties of a particular machine, in the long term it is necessary to measure in meters or nanometers. National laboratories are now finding that it is by no means a simple exercise to measure and identify the position of points on a 10 cm square with an accuracy of 10 nm or better. This is the level of accuracy and precision required of those national laboratories that are concerned with the testing of the commercial master grids that are used in the fabrication of masks for large-scale manufacture of integrated circuits.

Another example of extreme precision in manufacturing for the optoelectronic industries is the production of small aspheric lenses whose performance is diffraction limited, but whose dimensions are small. The production of the master mould for such lenses is possible with high-precision machining. Diamond machining, elastic-emission machining, and other processes now can produce surfaces smooth at the nanometer level. Intimately linked to the manufacture of objects having such properties is the measurement and testing of them. New optical devices now exist to measure surface profiles and at least one of them can observe large-scale surface structure at the level of tens of picometers.

The need for rapid inspection of complex objects manufactured to high precision by the new generations of numerically controlled machines has led to the development of coordinate-measuring machines. These machines are designed to measure the spatial coordinates of any point within a volume of up to 1 m^3 with an accuracy of about 1 μm. The calibration of such machines and the design of test objects for them is now a major activity of many national laboratories. The new "nanometrology" will require the development of new, more accurate techniques for surface profile, roundness, and diameter measurement. In these latter domains, existing optical or mechanical-contact methods for identifying the position of a surface are unlikely to be adequate. In order to identify the position of the surface of an object at the nanometer level it will be necessary first to define more carefully what it is meant by a surface and second to apply new methods, perhaps based upon the new tunnelling devices, to indicate contact.

Even if we can define what we mean by a surface and have devices that can detect its proximity, it is still necessary to be able to servo-control tools, work pieces and different parts of the device to maintain the required relative positions of all the component parts. The existing displacement detectors will have to be pushed to their limit. Capacitance devices are, of course, sensitive detectors of position but are difficult to make linear over a long range, and greater care is needed to avoid forces being applied to the object being displaced. Silicon cell detectors are not very sensitive at the level of fractions of a nanometer and, in any case, it can be difficult to supply enough light to obtain a sufficient signal-to-noise ratio without developing too much heat. Tunneling devices appear to be the most sensitive but have an infinitesimal range. Silicon X-ray interferometers are perhaps equally sensitive but are very difficult to adjust. Thus in the areas of length metrology, the advanced technology will require the ultimate in precision measurement. It will certainly have a great influence on the practical realization of the definition of the meter and the activities of the national laboratories in this field.

In order to detect relative movements, between different parts of an optical interferometer, of parts in 10^{18} to 10^{21}, great advances have been made and still need to be made in servo-control, position detection, and in ways of agumenting the signal-to-noise ratio in interferometers.

Why precise measurements and greater accuracy

We need to be able to make precise measurements for two reasons :

— to test fundamental physical theories of matter and the universe ;

— to provide the basis for the application of these tested physical theories to practical life through advanced technology.

We should continually strive for greater accuracy because advanced technology by its very nature is continually searching for greater efficiency and improved performance in all of its products. This inevitably results in continually increasing demands being placed on all of the factors contributing to efficiency and performance—one of these factors is measurement capability.

Needless to say, improved measurement accuracy leads to improved efficiency in manufacturing high-technology products. It must be obvious that being able to make a measurement to a given accuracy in only one tenth of the time will improve the efficiency of the process that relies upon that measurement. Such an increase in speed can only come about, however, by a greatly increased knowledge of the factors that previously limited the accuracy of the measurement, for example, improvement in signal-to-noise ratio that would probably have been acquired in the measurement system.

For international trade to be feasible, world-wide uniformity in measurement standards is essential. International trade in high-technology products, communication, and navigation networks, the exchange of scientific information, as well as a multitude of pure and applied scientific and technological projects carried out on an international basis, are all highly dependent upon traceability of measurements of national, and hence, to international measurement standards.

1.20. Establishing Calibration System

Market forces demand industry to ensure environment for supply of quality products to customers. Accurate measurements play a crucial role at each stage in the development and production of quality products. The aim of establishing calibration system is to develop internal metrology and calibration programmes to assure that the test and measuring instruments are maintained within desired accuracy. Systematic periodic checking of test and measuring instruments is thus becoming increasingly important to the development and maintenance of market competitiveness. This process of periodic checking against measuring equipments/standards of higher accuracy is termed as 'Calibration'.

An essential condition for establishment of calibration system is that the supplier shall control, calibrate and maintain inspection measuring and test equipment whether owned by the supplier, on loan, or provided by the purchaser, to demonstrate the conformance of product to the specified requirements, and further the equipments shall be used in a manner which ensures that measurement uncertainty is known and is consistent with the required measurement capability.

Important conditions for this purpose are :

(*i*) To ensure that the measuring equipment is capable of the desired accuracy and precision.

(*ii*) The calibration system should provide the means to directly or indirectly trace assigned values of measurement equipment to values in terms of nationally recognised standards.

(*iii*) Calibration should be carried out using measurement systems having adequate accuracy, stability and range to completely verify the performances of the calibrated item within its specified uncertainty limits.

(*iv*) The calibration procedure may be a document prepared internally, or by another agency, or by the manufacturer or a composite of the three. It is essential to designate and use documented procedures for all calibrations performed.

The contents for the calibration procedure are :

— Introductory description of the unit to be calibrated
— Preliminary actions prior to starting the calibration
— Measurement method used to verify the performance
— At table giving the specification tolerance of different parameters that can be measured by the unit and tolerance limits calculated.
— Listing of instructions to be performed.

(*v*) All test and measuring instruments should be securely and durably labelled, coded or otherwise identified to indicate its calibration status, *viz.* date of last calibration, date due for calibration, and the authenticity of calibration.

(*vi*) Access to adjustable controls/devices on measuring equipment whose setting affects the performance, should be sealed after calibration in order to prevent tampering by unauthorised personnel. Seals should be such that tampering is clearly apparent.

(*vii*) Test and Measuring equipment should be calibrated at periodic intervals established with the intent of achieving and maintaining a desired level of accuracy and quality.

(*viii*) Records should be maintained for all test and measuring equipment included in the calibration system.

(*ix*) It must be ensured that the environmental conditions (temperature, relative humidity, cleanliness, vibration, electromagnetic interference and voltage regulation of electric power) are suitable for the calibration and are maintained.

(*x*) Personnel performing calibrations of test and measuring instruments should have training in the area of job assignment, basic knowledge of metrology and calibration concepts, ability to follow instructions regarding maintenance and use of measurement equipment and standards.

(*xi*) The calibration control system should be subject to periodic audits conducted at a frequency and to the degree that assure compliance with all elements of the system procedures and documented requirements.

1.21. Geometry of Form or Shape

The measurement of geometrical values in modern engineering has become a factor of vital importance in the process of production due to higher and higher requirements for the accuracy of machined surfaces. Any machine is assembly of parts arranged in a definite relationship of each other. The surfaces of the various parts joining each other are called mating parts and their dimensions are called mating dimensions. The nature of the association required between the mating parts is determined by the conditions of operation of the machine and is called fit (*i.e.* more or less freedom in their relative movement of tightness in a fixed association). In the modern industry, mass production techniques are employed which aim at achieving strictly interchangeable assembly. Interchangeability concerns not only the size and form of parts, their position and surface finish, but the properties of the material of which they are made as well. In this book we shall be concerned with dimensional interchangeability only. (A strictly interchangeable part is one which can be assembled without selection, adjustment, or supplementary operations and which will function after assembly as stipulated by the manufacturing specifications, whereas an incompletely interchangeable part may require selection or adjustment, but will not require additional fitting or machining operation.)

In any machine, the following elements are to be inspected accurately for its functioning :

(1) Dimensional accuracy.

(2) Accuracy of geometrical form (which is usually a combination of flat, cylindrical, taper, spherical, and other surfaces) or surface macrogeometry.

(3) Accuracy of location of surfaces with reference to each other.

(4) Surface waviness.

(5) Surface roughness or surface microgeometry.

According to the form, the errors could be classified as :

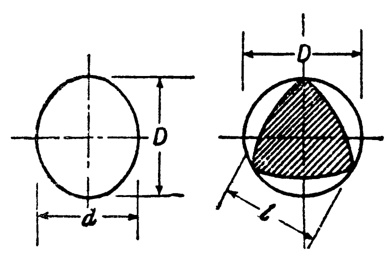
(*a*) *For cylindrical form*

In a transverse section.

(1) Oval form (out-of-roundness) :

(2) Lobed form.

The degree of ovality (out-of-roundness) is judged by the difference between the major and minor axes in a single cross-section. The lobed form is one in which the cross-section contour is composed of arcs drawn from different centres. The amount of lobedness is determined as the difference between the diameter of the circle D into which the lobed cross-section is inscribed and the distance l between the parallel planes tangent to the part.



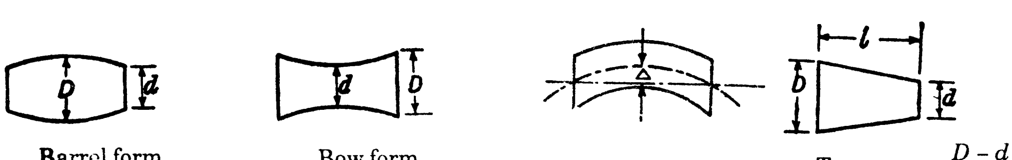
Ovality = $D - d$ Lobedness = $D - l$

Fig. 1.21

In a ligitudinal section :

(1) Barrel form ; (2) Bow (concave) form ;

(3) Curvature of the axis ; (4) Taper.



Barrel form
Barrelness = $D - d$

Bow form
Bowness = $D - d$

Curvature of axis = Δ

Taperness = $\frac{D-d}{l}$

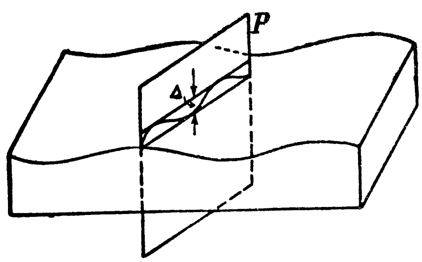
Fig. 1.22

The barrel or bow forms are judged by the difference in diameters at the middle and end cross-sections. The curvature of the axis in determined by the deflection of the axis. The taper is evaluated by the difference in diameters over a given length.

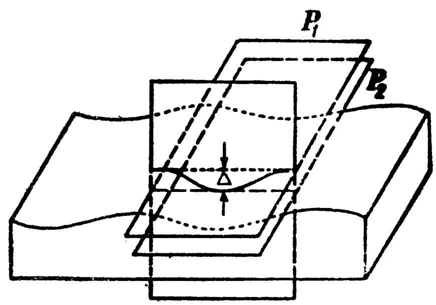
(*b*) *For flat surface*

(1) Lack of straightness ; (2) Lack of flatness.

Lack of straightness in a flat surface is the distance between two parallel lines located in a plane *P* square with the tested surface *e.g.*, in Fig. 1.23 (*a*) plane *P* intersects the surface in the required direction and two lines are drawn to enclose the section profile of the testes surface. The lack of straightness in Fig. 1.23 (*a*) is represented by Δ.



(*a*) Lack of Straightness



(*b*) Lack of Flatness

Fig. 1.23

Lack of flatness is expressed as the distance between the parallel planes P_1 and P_2 which enclose the tested surface between them. [Refer Fig. 1.23 (*b*)]

According to the relative location of surfaces, the errors could be classified as follows :

(1) Measurement ; (2) Radial run out ;

(3) Axial run out ; (4) Non-parallelism of axes ;

(5) Incorrect location of intersecting axes ; (6) Surfaces not parallel with each other ;

(7) Surfaces not square with each other.

Misalignment is the parallel deviation Δ of axes relative to one another. It is also the amount of cocking between two axes determined as the distance Δ between the centres of the holes on the tested length *l*. (Refer Fig. 1.24).

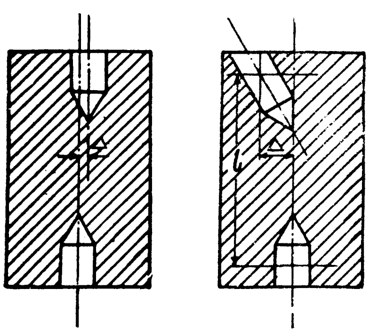


Fig. 1.24. Misalignment.

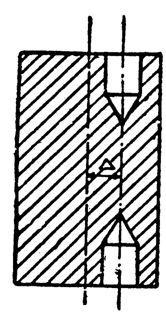


Fig. 1.25. Radial runout.

Radial runout is the maximum difference between the actual physical centre of the body and its axis of rotation. It may be as a result of either misalignment of axis, ovality, lobed form or curvature of axis.

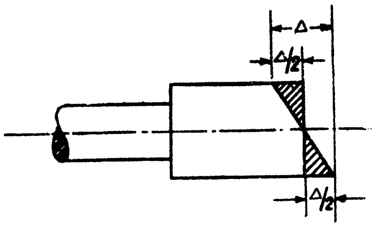


Fig. 1.26. Axial runout or slip.

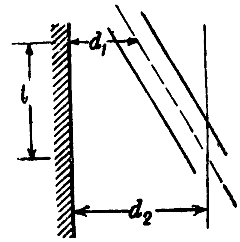


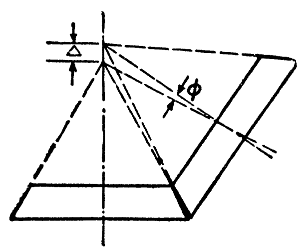
Fig. 1.27. Non-parallelism of axes.

Axial runout or slip is the maximum deviation Δ of an end surface from a plane square with axis of the part (Refer Fig. 1.26).

Non-parallelism of axes is the difference in the distance d_1 and d_2 between the axes measured in cross- section square with one axis and at the given distance l apart from each other. (Refer Fig. 1.27).

The amount by which surfaces are not square with each other is the deviation from a right angle of the angle between the surfaces.

The amount by which surfaces are not parallel with each other is the difference in distances between the surfaces measured at a given distance.



Incorrect location of intersecting axes
Fig. 1.28

Incorrect location of intersecting axes is determined by the angular deviation ϕ from the specified angle of intersection and the deviation Δ from the point of intersection.

1.22. Optical Principles

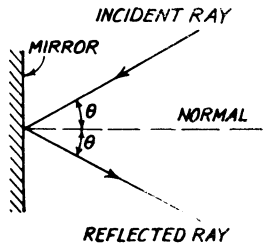
More and more precision measuring instruments employ optical principles and as such brief study of optical principles is considered essential.

The purpose of the optical system is to enable an image of the object being examined to be formed, generally to permit particular measurements to be made. The classes of measurements to which optics may be readily applied are those dealing with length, angle and irregular profiles.

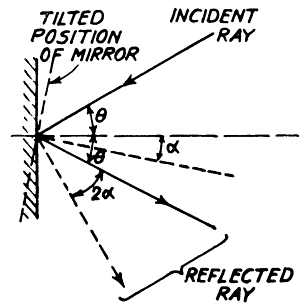
The fundamental optical principles of importance in the design of precision measuring equipment are : (1) reflection, (2) refraction and (3) interference phenomena.

Light is propagated as an electromagnetic radiation having a very short wavelength, which varies according to the colour of light. At the violet end of the spectrum the wavelength is about 0.4 μm and at the red end about 0.7 μ m. White light is a mixture of all the colours of the spectrum. Rays of light travel in straight lines provided the medium in which they are transmitted is of uniform character.

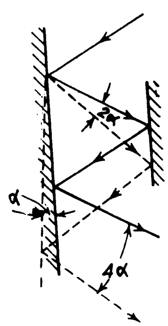
When reflection occurs at a plane surface, the angle between the normal to the surface and the reflected ray is equal to the angle between the normal and the incident ray. This is shown in Fig. 1.29 (*a*). If the reflecting surface is tilted through an angle α, the normal also moves through this angle. Then, as shown in Fig. 129 (*b*), the angles of incidence of reflection each become equal to $(\theta + \alpha)$ and the total angle between the incident and reflected ray becomes $(\theta + \alpha)$. There is thus an increase of 2α in the total angle and a magnification of two is obtained. If, as shown at Fig. 1.29 (*c*), the reflected ray is again reflected from the tilted mirror by a second fixed mirror, the change in the angle of the final reflected ray becomes 4 α. In some instruments the second mirror is arranged to tilt through the same angle α, thereby giving a magnification of eight.



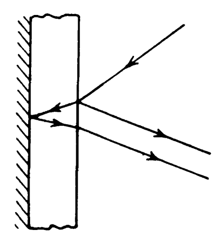
(*a*) Reflection at a plane surface.



(*b*) Reflection from tilted mirror.



(*c*) Multi reflected.

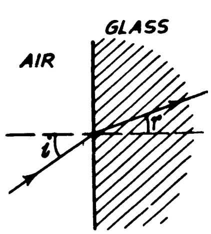


(*d*) Reflection from back silvered glass.

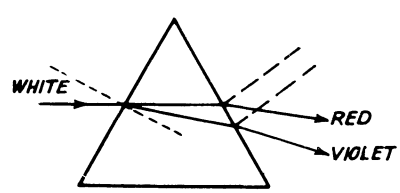
Fig. 1.29. Principles of light reflection from plane mirrors.

Most mirrors in everyday use consist of a piece of glass with the rear surface silvered and varnished over to protect it from damage.

Such mirrors are rearly suitable for use in metrological instruments because, as shown in Fig. 1.29 (*d*), there are two reflections, one from the front surface of the glass and one from the back silvered surface of the glass and one from the back silvered surface. Although the front reflection may be much weaker than that from the silvered surface, it almost coincides with the latter and makes it less distinct. Accurate mirrors for optical work consist of glass with the front surface coated with a thin deposit of a metal which has good resistance to corrosion. The reflecting surface is thus exposed and care must be taken in cleaning it.



(*a*) Refraction through glass.



(*b*) Refraction through prism.

Fig. 1.30. Principles of light refraction.

When a ray of light passes from one transparent medium to another, it changes direction. Fig. 1.30 (*a*) shows a ray of light entering a block of glass. It will be seen that the ray is bent towards the normal to the surface separating the glass and air. A ray passing from glass to air is bent away from the normal. The amount of bending depends upon the angle of the incident ray and upon the relative densities of two media. It i denotes the angle of incidence and r the angle of refraction, then $\sin i/\sin r$ is a constant known as the refractive index.

The refractive index depends upon the wavelength of the light, being larger for the shorter wavelengths. This causes more bending of light at the violet end of the spectrum that at the red end and hence the separation of white light into its component colours. When white light passes through a parallel sided piece of glass, recombination of the colours occurs at exit ; but if through a prism, as shown in Fig. 1.30 (*b*), the colours remain separated and can be seen on a screen.

A number of different kinds of internal reflecting prisms may be employed in measuring instruments. The use of triangular prisms for deviation of 90°, 180° and 360° can be seen in Fig. 1.31.

One of the most important prisms of this class is the "Pentag" (pentagonal prism), a constant deviation prism used on some interferometers. It is also used as the basic feature of the optical square. An outline of one form of Pentag is shown in Fig. 1.31. The emergent ray is always at right angles to the incident ray, owing to the internal reflections undergone by the light ray. However, these internal reflections are the result of silvering the faces *SS* shown in Fig. 1.31, and are not due to the theory of the critical angle.

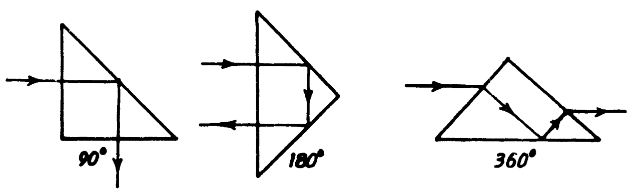


Fig. 1.31. Principles of internal reflecting prisms.

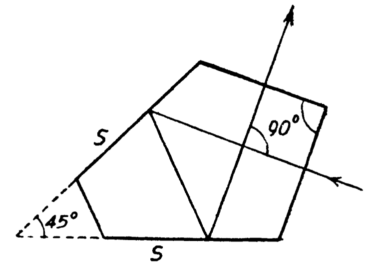


Fig. 1.32. Principle of "Pentag".

A lens can be regarded as an infinite number of parts of prisms having different angles. A convex lens causes a beam of light to converge, whereas a concave lens causes divergence. Fig. 1.33 shows a parallel beam of rays entering a convex lens, which brings the beam to a focus. From the concave lens, shown at Fig. 1.34 the parallel rays diverge and appear to come from a point behind the lens. Such a lens will not form an image on a screen, but only a virtual image which can be seen by looking through the lens.

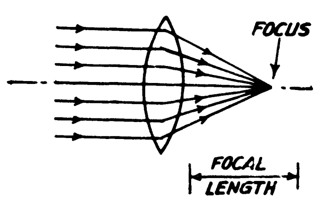


Fig. 1.33. Pinciples of light convergence.

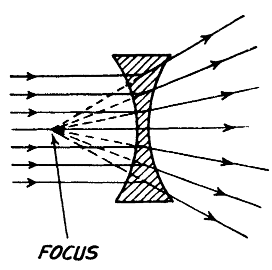
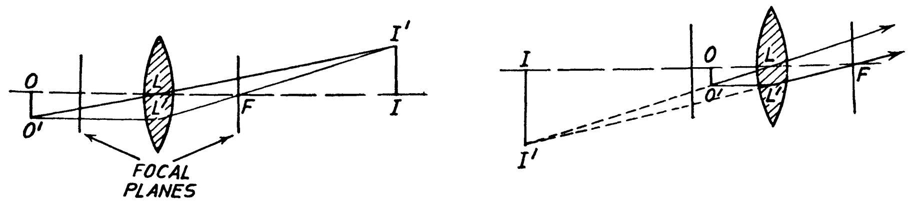


Fig. 1.34. Principles of light divergence.

The most important dimension associated with a lens is its focal length, that is, the distance from the lens to the point at which it brings parallel rays to a sharp focus. Knowing this distance the effect of a lens upon a beam of light can be determined. In Fig. 1.35 (*a*), rays of light from an object OO' pass through a convex lens and form an inverted image of the object at II'. The size and position of the image is found by the following construction. The line $O'L$ through the centre of the lens is drawn and continued beyond the lens. The line $O'L'$ is then drawn parallel to the axis of the lens and from L' a line $L'F$ produced is drawn through the focal point to meet the first line in I'.

This construction could be applied to every point on the object OO' and would form corresponding point on the image II'. The ratio of the size of image and object are given by the relation.

$$\frac{II'}{OO'} = \frac{IL}{OL}$$

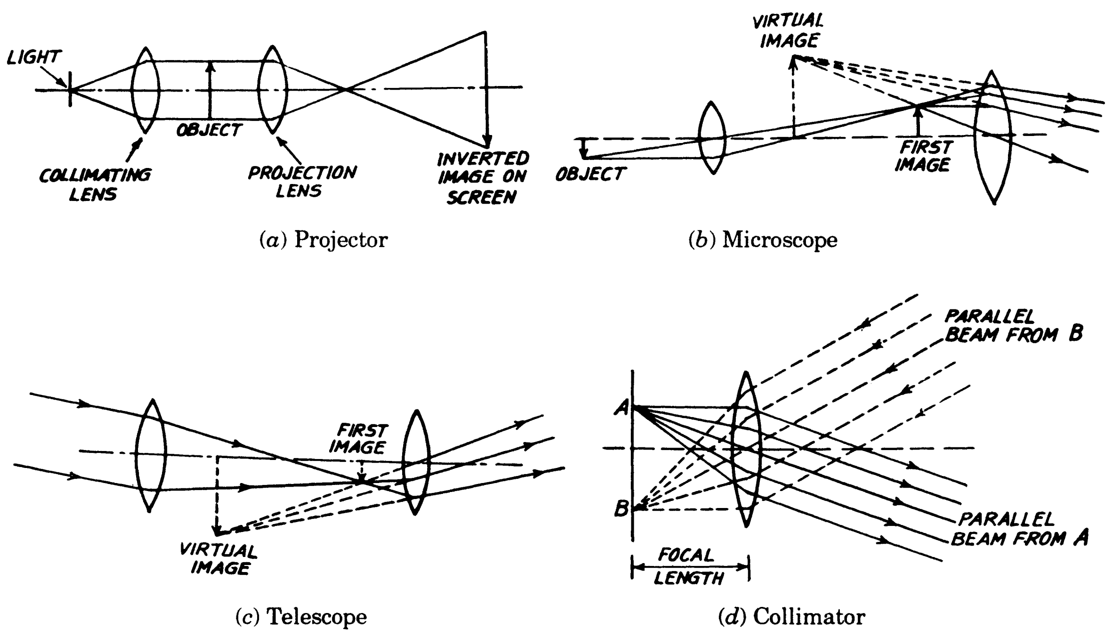


(a) (b)

Fig. 1.35. Principle of image formation by a convex lens.

If the object is brought nearer to the lens the image is larger and farther away. When the object is brought into the focal plane, rays from the lens become parallel and no image is formed. By bringing the object still near to the lens, a virtual, upright, image is formed as shown in Fig. 1.35 (b).

Simplified diagrams of the optical principles of some instruments are shown in Fig. 1.36. In all these, each lens is shown as single piece of glass, although, in practice, it may consist of several pieces. By combining into one unit several lenses made of glass having different refractive indices, various errors, such as the formation of coloured rings, can be reduced.



(a) Projector (b) Microscope

(c) Telescope (d) Collimator

Fig. 1.36. Principles of image formation.

The inherent disadvantages found in the mechanical pointer, as weight, bending properties, friction etc., may be overcome by using an *optical lever* shown in Fig. 1.37. The principle of this device involves the movement of a mirror (fixed to an appropriate feature of the instrument concerned) on which a beam of light is directed. The movement of the mirror is related to, and can be read off a scale, the image of which moves past a fixed fiducial line mounted in the eyepiece of a telescope. The beam of light forms wieghtless lever. An important advantage obtained when using optical lever is that the reflected beam deflects through twice the angle of rotation of the mirror, thus giving an automatic magnification.

A screen upon which a spot of light is focused may also be used to avoid *parallax* errors (which result, with mechanical indicators, from different readings obtained when the observer's eye is moved to different positions). Alternatively, some instruments incorporate a fixed fiducial mark on the screen. An image of the scale moves over the screen, but only part of the scale is visible to the observer for a given position of the mirror.

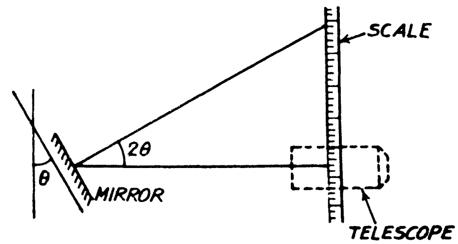


Fig. 1.37. Principle of an optical lever.

1.23. Quality Improvement Programmes

Implementation of quality improvement programmes results into :

— dramatic reduction of defects

— improvement in overall product reliability

— dramatic decrease in the cost of quality

— increased customer satisfaction

— increased overall market share.

The philosophy behind quality improvement program is depicted by following :

— Quality is free since it pays for itself through reduced operating costs and increased sales through satisfied customers.

— Defect free products are possible and must be achieved. Acceptable Quality Levels (*AQL's*) are no longer good enough.

— Prevention is better than inspection *i.e.* quality must be built in and not inspected in. This is possible by eliminating operation and process variables.

— Everyone is a link in the quality chain, *i.e.* total employee involvement is essential, and teamwork is the basis of success.

— The concept of Total Business Quality (*i.e.* only a quality business can deliver a quality product) need to perculate throughout the plant. A total quality approach to the whole business is the best strategy.

The sequence of developments in regards of present status of metrology in regard to Quality is as under :

— Conventional inspection—sorting good from bad after manufacture. This is now a totally outmoded and inefficient philosophy and practice.

— Operator quality control—A technique in which operator is responsible for the quality he produces by provision of measurement/gauging equipment with the aim of determining trends and thus preventing defects from occurring.

— Accuracy capability studies on production machinery—An implicit acceptance, if not full recognition of deterministic performace of production machines leading to selection of "accuracy capable" machines and probable use of statistical sampling techniques (*SQC*).

— Post process measurement, analysis, and feedback control—It is frequently based on strictly sequential measurement of parts (from which patterns of performance can more readily be recognised).

— In process measurement and control—In it the speed of response of the closed-loop error feed back servo-system is at its highest.
— Adaptive control—It can compensate for relatively rapid trends/parameter changes like grinding wheel wear.

1.24. Managing Measuring Equipment

Measurement is the process of assigning a value to a given physical quantity. Quality is the capability of a product (or a service) to meet stated and implied needs. Measurements have significant role in product quality through the testing of products against a relevant specification, after completion of manufacture. In many cases tests are carried out during manufacture, on the partially assembled product or on key components, to ensure that the manufacturing process is going as planned and to enable any necessary process adjustments to be made.

Measurements have definite role in achieving product quality, leading to industrial competitiveness, consumer protection and related benefits. Measurements also have a vital part to play in enhancing quality in the more global sense of quality of life. The accuracy of an item of measuring equipment is established by testing that equipment in the appropriate way, using a more accurate measuring instrument. The accuracy of the measurement standard concerned may in turn be established, in a similar way, by calibration of the standard against a higher, more accurate standard, and so on, through an unbroken chain of calibrations, stretching back to the national measurement standards held at NPL.(measurement traceability). The national measurement standards held at NPL form the anchor for traceability chains serving different levels and sectors throughout the country. Traceability of measurement is essential, if accuracy of measurement is to be meaningfully assigned, and if measurements made on different instruments or at different times and locations are to be validly combined or intercompared.

Credibility of a measurement result deserves good attention. For example, a laboratory may possess accurate equipment, properly calibrated, but credibility will be lost if measurements are carried out with the equipment at the wrong temperature, or if measurement staff is insufficiently skilled, supervised or briefed in their tasks. Even where a measurement has been carried out satisfactorily, its usefulness may be undermined due to the result being reported or recorded in an ambiguous or misleading way. Only when there exists authenticated measurement traceability and when the measuring equipment is under proper control over all other aspects influencing credibility, can there be proper measurement assurance, giving overall confidence in a measuring equipment's capability to produce correct measurement results.

The management of measuring equipment requires the establishment of a system to demonstrate one's capability to provide reliable measurement results. The elements of the system demand an orderly approach to acquisition, calibration, maintenance, use and periodic recalibration of all measuring equipment. All equipment used in the measurement of characteristics of the product which affects its ability to comply with the specified requirement must be controlled, calibrated and maintained. Measuring equipment shall have the accuracy, stability, range and resolution required for the intended use. It should be ensured that the risk of measuring equipment producing results having unacceptable errors remains within acceptable bounds.

It is essential to establish and maintain an effective documented system for the managing, qualification and use of measuring equipment including measurement standards. The system must provide for the prevention of errors outside the specified limits of permissible error, by prompt detection of deficiencies and by timely action for their correction.

In performing measurements and in stating and making use of the results, it is required to take into account all significant known uncertainties in the measurement process including those that are attributable to measuring equipment (including measurement standards) and those contributed by personnel, procedures and environment.

Any item of measuring equipment that has suffered damage ; that has been overloaded or mishandled ; that shows any malfunction ; whose proper functioning is subject to doubt ; that has exceeded its designated qualification interval ; the integrity of whose seal has been violated ; must be removed from service by segregation, prominent labeling or marking. Such equipment should not be returned to service until it has been repaired and again qualified.

Access to adjustable devices on measuring equipment, whose setting affects the performance, has to be sealed or otherwise safeguarded immediately following the calibration and qualification in order to prevent tampering by unauthorized personnel. Seals must be designed in such a way that tampering is clearly apparent.

A system for receiving, handling, transporting, storing and despatching the measuring equipment, must be established and maintained in order to prevent abuse, misuse, damage and changes in dimensional and functional characteristics.

1.25. Measurements and Traceability

Measurement is necessarily a science of comparison. For a measurement result to be meaningful, it has to be traceable to national standards. The SI system of units consisting of 28 units (7 base, 2 supplementary and 19 derived units) are the basis of all modern measurements. The SI is a set of definitions. National laboratories are mandated to conduct experiments to realise and maintain the national standards of measurements. Every measurement has to have a linkage to the national standard. Traceability is a system of transferring the SI unit from the point of definition to the user. The use of hierarchical calibration system for achieving traceability is a necessary condition for credible measurements and it should be coupled with an appropriate degree of measurement quality assurance programme. The credibility of measurement results can be taken care of by use of educated and trained personnel, employing suitable measurement procedures, ensuring calibration status and maintenance of measuring equipment, and maintaining records for repeatability of measurements.

Accreditation (third party assurance about technical competence of a calibration laboratory) is done through an assessment process for laboratories. The overall programme of calibration of equipment needs to be designed and operated so as to ensure that all measurements made in a laboratory are traceable to national standards. The regulatory requirements for measurement traceability as prescribed must be strictly followed. The necessary condition for achieving traceability is that all the test and measuring equipment are calibrated by a laboratory whose standards have linkage to national standards.

Competent calibration and traceability of measurements are essential. The purpose of calibration is to limit the maximum error of the metrological characteristics of calibrated standards or instruments that enters into uncertainty levels of subsequent measurements.

1.26. Quality, Standardisation, Testing and Metrology (QSTM)

Global trade depends on quality and metrology to establish confidence between customers and supplier. Global trade is open to all and in order to take part effectively in today's global economy, QSTM activities are essential to improve productivity and ensure social and economic development. The basic concerns for QSTM programme are to ensure competitiveness, consumer protection (health and safety), and the protection of the environment. Competitiveness is possible by taking care of work culture, productivity, quality and environment. To meet customers requirements the new challenge is the production of high quality products, conformity to international standards, testing certification and high accuracy of measurements. Metrological practices have to take care of the increasing demand for international uniformity of measurements and the extension of normalisation and quality control based on metrology, the extension and globalisation of trade and to reduce all kinds of barriers, the continuous advent of new technologies and products calling for major reduction of uncertainties in measurements, the extension of metrology to new physical quantities, and the reinforcement of the presence of accurate metrology in fields of social importance such as environmental control and medical care.

The national measurement system provides a coherent formal system which ensures that measurements can be made on a consistent basis throughout the country. The contribution of International Standards Organisation in establishing standards and guides, and their transparent implementation by countries with the help of independent accrediation organisation has helped building the confidence between customer and supplier across international borders.

Quality Council of India has been established in India to implement accrediation system in line with international practice and to oversee and regulate conformity assessment process.

Conformity assessment organisation like Quality Council of India and Accrediation Boards establish rules and regulations to be followed by companies in the business.

SOLVED PROBLEMS

Q. 1.1. What is the difference between accuracy and uncertainty, and precision and accuracy ?

Ans. Every part has some true dimension and the purpose of measurements is to ascertain that true dimension. But for numerous reasons, the true dimension can never actually be determined—it can only be approximated. Accuracy of an instrument is closeness to the truth ; *e.g.* if an instrument of accuracy ± 0.01 mm indicates the dimension of a part is 20 mm, it means that true dimension could lie between 19.99 and 20.01 mm. Thus saying accuracy of ± 0.01 mm means that the measurement can be inaccurate by ± 0.01 mm or there is uncertainty about the true value to the extent of ± 0.01 mm. It would be noted that though the terms accuracy and uncertainty are complementary terms but they are used synonymously.

There exists a lot of confusion between the terms precision and accuracy. It is important to note that while the accuracy is concerned with closeness to true value, precision has no such connotation and it represents the degree of repetitiveness, and refers to a group of measurements rather than a single measurement. If an instrument is not precise, it will give different (widely varying) results for same dimension when measured again and again. Such an instrument thus is considered non-trustworthy. The first and fundamental requirement of any good instrument to be effective is that it should have adequate repeatability or precision. If an instrument is sensitive, it is likely to give different readings due to random influences like fluctuating temperature, presence/absence of dust, variation of gauging force. Thus if the measurements obtained are random in nature, and do not show any increasing or decreasing trend, then they can be characterised by two parameters, *viz.* average and standard deviation. The standard deviation, *i.e.* measure of spread represents the precision, and the closeness of average value to the true value refers to the accuracy of the measurement. Various influences can affect the precision and various sources of errors can affect the accuracy of measurement and, therefore, the measurements should be taken with great care and every effort made to eliminate fixed errors. The random errors can be minimised by defining and maintaining the changing conditions like temperature, gauging force etc. Therefore, many (minimum three) readings should be taken to get accurate results.

Q. 1.2. What is the relationship between sensitivity and range ? What is the disadvantage of very sensitive instruments ?

Ans. Sensitivity refers to minimum change in value that the instrument can reliably indicate. Obviously if an instrument is sensitive to read 0.01 mm and considering the limitation of length of the scale which may have about 100 divisions, each division representing 0.01 mm, the range can be 0.01 × 100, *i.e.* 1 mm. If a still more sensitive instrument (say 10 times more sensitive) is used then range has to be reduced to one-tenth. In other words, range and sensitivity have inverse relationship. It may be appreciated here that there is no advantage in using an instrument more sensitive than requirement ; in fact it is likely to be a disadvantage.

More the sensitive a gauge is, more susceptible it will be to extraneous influences, particularly vibration. It thus becomes very difficult for the operator to get reliable reading, and in fact it becomes a source of irritation to him. Another serious disadvantage is that the operator starts placing too much reliance in the value indicated by that instrument, *e.g.* though the operator may be interested in a dimension upto ± 0.01 mm but if he takes reading with instrument of ± 0.001 mm sensitivity, he is tempted to feel that reading exact dimension is as given upto third digit which infact may be meaningless unless the geometry of the part is good and the conditions of the instrument justify faith in the last digit.

Q. 1.3 One manufacturer of a co-ordinate measuring machine has indicated its accuracy as :

3 σ (three sigma)	**accuracy : ± 0.003 mm**
2 σ	**accuracy : ± 0.002 mm**
1 σ	**accuracy : ± 0.001 mm.**

What do you understand by this statement ?

Ans. More the complex a machine is, more are the possibilities of errors that effect the accuracy of machine. The errors in such a machine could be of the following nature : errors in straightness and squareness of ways, true running of bearings, deflection of parts loaded in machine, temperature gradients, errors in scales and reading heads and other random errors. Thus the accuracy of such a machine cannot be quoted simply as a plus or minus value but it has to be quoted in statistical terms, *i.e.* state it as a high or low probability of being correct. The statement given above means that if 1,000 readings are taken with this machine then 99.7% or 997 of them will be within ± 0.003 mm of the true value, 95.4% or 954 will be within ± 0.002 mm of the true value and about 68% within ± 0.001 mm of the true value. In effect, with highly complex machines, this is the only meaningful way to express the accuracy.

Q. 1.4. Define the following terms so as to bring out the difference between them clearly :

(*i*) (*a*) **Quantity (Parameter)** (*b*) **Base Quantity** (*c*) **Influence quantity** (*d*) **Derived Quantity** (*e*) **True value of quantity.** (*f*) **Conventional true value of quantity.**

(*ii*) **Method of** (*a*) **direct measurement,** (*b*) **indirect measurement,** (*c*) **non-contact measurement,** (*d*) **fundamental measurement,** (*e*) **measurement by comparison,** (*f*) **differential measurement,** (*g*) **null measurement.**

Ans. (*i*) (*a*) *Quantity (Parameter).* It is the attribute of a phenomenon of a body which is capable of being distinguished qualitatively and determined quantitatively, *e.g.* length, temperature, pressure etc.

(*b*) *Base quantity.* It is the designation of quantities which in a system of quantities are accepted as being independent of one another and by means of which the quantities derived from them in that system may be expressed by equations of definition.

(*c*) *Influence quantity.* It is the quantity which is not directly of interest for measurement but is measured to represent some other quantity (of interest) as it influences the value of the quantity to be measured.

(*d*) *Derived quantity.* It is the quantity defined in a system of quantity as being a function of the base quantities of that system.

(e) *True value of a quantity.* It is the value which characterises a quantity determined perfectly in the conditions which exist at the moment when the value is observed. It is an ideal concept and, in general it can't be determined.

(f) *Conventional true value of a quantity.* It is the value approaching the true value of quantity and for all practical purposes may be considered as true value.

(ii) (a) Method of direct measurement is one in which the value of a quantity to be measured is obtained directly without the necessity of carrying out supplementary calculations based on a functional dependence of the quantity to be measured in relation to other quantities actually measured. For example, measurement of length by vernier caliper or by micrometer screw gauge.

(b) Method of indirect measurement is one in which the value of a quantity is obtained from measurements carried out by direct method of other quantities, connected with the quantity to be measured by a known relationship. For example, measurement of angle by sine bar and slip gauges.

(c) Method of non-contact measurement is one in which the sensing element is not placed in contact with object whose characteristics are to be measured ; *e.g.* measurement of diameter by pneumatic comparator.

(d) Method of fundamental measurement is also known as method of absolute measurement which is based on the measurements of base quantities entering into the definition of the quantity.

(e) Method of measurement by comparison is one which is based on comparison of the value of a quantity to be measured with a known value of the same quantity or a known value of another quantity which is function of the quantity to be measured.

(f) Method of differential measurement is based on the comparison of the quantity to be measured with a known quantity of the same kind but slightly different from that to be measured and measuring the difference between the values of these two quantities. Generally this is the most accurate method as it does not depend on the zero error of instrument, accuracy of calibration throughout the range.

(g) Method of null measurement is one in which the known quantity is so adjusted that difference between it and the quantity to be measured becomes zero. In this method, the difference between these two qualities is fed to an amplifier which drives a servomotor which in turn changes the value of the known quantity and also drives a pointer. At balanced condition, the pointer indicates the exact value of the quantity to be measured.

Q. 1.5. In gauging, the aim is only to ensure whether a component lies within tolerable limits, irrespective of its actual size. Such a method is called measurement by attributes. In measurement by variable systems, actual size is measured with a precise measuring instrument. Compare the characteristics of two systems.

Ans. Table below gives comparison of characteristics of two methods of measurements.

Characteristic	*Measurement by Attributes*	*Variable measuring system*
Type of instrument required	Fixed gauges or comparators	Precise measuring instruments
Cost of measuring instrument	low	high
Overall cost of measurement	low	high
Result of measurement	Good or bad, accepted or rejected	actual size precisely
Information value per observation	limited	can be used for many purposes
Skill of operator	unskilled	skilled
Speed of use	fast	slow

Q. 1.6. What is the difference between single sample test and multi sample test in connection with minimisation of the sources of errors in results of measurements ?

Ans. In measurement system, attempts are always made so that the results of measurement approach the true value, *i.e.* the errors in measurement which are inevitable in the system of measurement should be minimised. One of the methods to minimise errors is to take number of readings for the same parameter or attribute, and take the mean value. If the various observations are made again and again by the same person using same instrument then the results obtained are called to have been collected in a single sample test. However, if same parameter or attribute is measured a number of times by using alternate test conditions (like different operators, different instruments and procedures etc.) then the procedure is called multi-sample test. Multi-sample tests though being more costlier than single-sample test are more reliable as these eliminate controllable errors like personal errors, instrument zero error etc. However, in most of the cases, a number of readings under single sample test with statistical technique are found to be adequate.

Q. 1.7. Define the following terms :

(*i*) Error and correction, (*ii*) Systematic and random errors, (*iii*) Parasitic and illegitimate errors, (*iv*) Absolute and relative errors, (*v*) Standard deviation (σ) of a single measurement in a series of measurements and σ of the arithmetic mean of a series of measurements, (*vi*) Uncertainty of measurement and inaccuracy of measurement.

Ans. (*i*) *Error and correction.* While error is the disagreement between the result of measurement and the actual value of the quantity measured ; the correction is the value which should be added algebraically to the measured value to obtain correct result.

(*ii*) *Systematic and random errors.* Systematic error remains constant in absolute value and sign when a certain parameter is measured several times under the same conditions or it may vary according to a specified law if the conditions change. Systematic errors are, therefore, regularly repetitive in nature and result from improper conditions or procedures that are consistent in action. The causes of these errors may be known or unknown. Error from most of the known sources can be controlled. The random errors, unlike systematic errors, vary in an unpredictable manner both in absolute value and sign when a certain parameter is measured several times under the same conditions. These are inherent in the measuring system and as such can't be eliminated but the result of measurement can be corrected.

(*iii*) Parasitic error results from incorrect execution of measurement. The illegitimate error results due to blunders, errors in computation and offsets the final results so much that it can be detected.

(*iv*) Absolute error is the algebraic difference between the result of measurement and the value of comparison. If the value of the comparison is the conventionally true value of the quantity measured, it is known as true absolute error. If a series of measurement are made then the algebraic difference between one of the results of measurements and the arithmetical mean is known as apparent absolute error. Relative error is the quotient of the absolute error and the value of comparison (which may be true value, conventional true value or arithmetic mean of a series of measurements) used for the calculation of that absolute error.

(*v*) Standard deviation or root mean square deviation of a single measurement in a series of measurements is the parameter characterising the dispersion of the results obtained in series of n measurements of the same value of a quantity measured, and is expressed by the formula

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})}{n-1}}$$

where x_i = ith result of measurement, and $\bar{x}$ = arithmetic mean of n results.

Standard deviation of the arithmetic mean of a series of measurements (σ_r) is the parameter characterising the dispersion of the arithmetic mean of a series of independent measurements of the same value of a quantity measured and expressed by

$$\sigma_r = \frac{\sigma}{\sqrt{N-1}}$$

where σ = R.M.S. deviation of a single measurement of a series,

N = No. of series of measurements.

(*vi*) Uncertainty of measurement represents the dispersion of the result of measurement defined by the limits of the error. Inaccuracy of measurement is expressed by all sorts of limiting errors of measurement including all systematic errors as well as limiting random errors.

Q. 1.8. Describe the following types of errors and how they can be taken care of ?

(*i*) **Environmental error**

(*ii*) **Error due to deformation of stylus and workpiece**

(*iii*) **Error due to application of measuring force**

(*iv*) **Parallax error**

(*v*) **Error due to non-alignment of centre lines of the workpiece and the measuring instrument**

(*vi*) **Error due to backlash and friction.**

Ans. (*i*) Environmental error occurs if the measurement is carried out at conditions other than standard ambient conditions of 20°C temperature and 760 mm of Hg barometric pressure, at which instruments are calibrated, but these can be easily accounted for. Temperature of instrument of workpiece may deviate from standard value of 20° either due to change in ambient temperature itself or due to handling. Error in measurement at different temperatures (say, instrument as t_1 from 20°C and workpiece at t_w from 20°C for workpiece of length '*l*' is = $l\ (\alpha_w t_w - (\alpha_i t_i)$ where, α_w and α_i are the coefficients of thermal linear expansion of workpiece and instrument respectively.

(*ii*) In stylus type instruments, the contact pressure between stylus and workpiece can deform both. Further deflection may also be there depending on the method of supporting workpiecs and the flexural rigidity of both workpiece and instrument. Scarr and Spencer gave the following formula to determine the value of deformation :

$$\delta = KP^{2/3}\left(\frac{1}{2R_1}+\frac{1}{2R_2}\right)^{1/3}\left(\frac{V_1+V_2}{2}\right)^{2/3}$$

where K = constant dependent on the ratio of geometry of the stylus and workpiece

P = stylus contact pressure

R_1 and R_2 are the tip radii of stylus and workpiece respectively

V_1 and V_2 are the constants depending on the materials of stylus and workpiece stylus and workpiece.

(*iii*) Application of measurement force deforms the workpiece as a result of which its dimension is altered. This type of error while comparing an unknown dimension with standard piece can be determined by the relation.

$$\text{Error} = L\left(\frac{F}{A_wE_w}-\frac{F}{A_sE_s}\right)$$

Where L = length to be measured, and F = measuring force

A_w and A_s are the cross-sections of workpiece and standard respectively

E_w and E_s are the values of modulus of elasticity of materials of workpiece and standard.

(*iv*) Parallax error occurs when the scale and pointer are not in the same plane, *i.e.* they are separated from each other and the reading is not taken normal to the plane of the scale. Referring to Fig. 1.38, say, pointer is located at distance l from scale and observer's eye is at distance L from scale. SN is normal to scale and if observer's eye is not along this line but at E (*i.e.* at angle θ with normal to scale) then while he views reading S at the scale, he sees reading corresponding to projection of point A (on the pointer) on the scale and thus PA becomes the error, and this error is equal to

$$e = \frac{l}{L} \times NE = \frac{l}{L} \times L \tan\theta = l \tan\theta$$

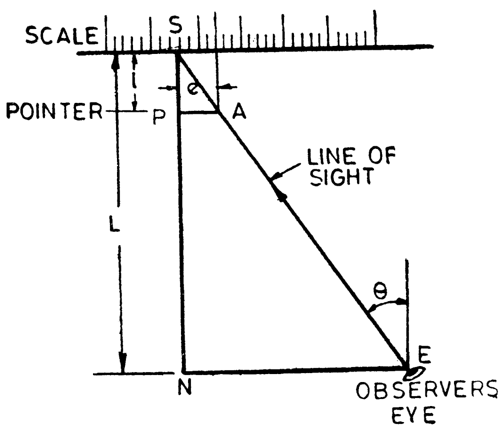


Fig. 1.38. Parallax error.

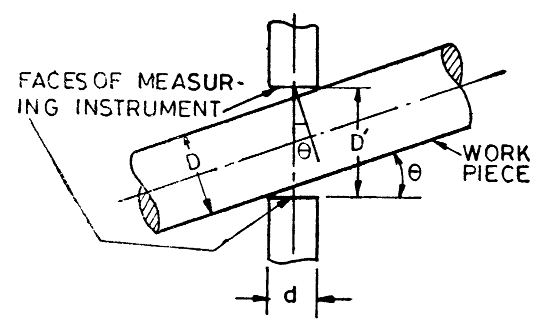


Fig. 1.39. Misalignment error on floating carriage type measuring instrument.

For least error, l should be minimum possible. Value of θ can be reduced to zero by placing mirror behind the pointer which ensures normal reading of scale.

(*v*) Many times the centre lines of workpiece and measuring instrument may be misaligned which also introduces error in measurement. Fig. 1.39 shows a simple commonly encountered case. In this case, workpiece is inclined at angle θ w.r.t. normal line between faces of measuring instrument and as such diameter D is measured as D'.

$$D' = D \sec\theta + 2\left(\frac{d}{2}\tan\theta\right) = D\sec\theta + d\tan\theta$$

$$\text{Error} = D' - D = D(\sec\theta - 1) + d\tan\theta.$$

(*vi*) Error on account of backlash and friction can be detected and corrected by observing reading first by increasing the instrument span from servo to desired value, and then decreasing the span from wide open to the desired value.

Q. 1.9. Discuss the characteristics of various materials for fabrication of different parts of measuring instruments.

Ans. Best possible materials should be used in manufacturing precision measuring instruments in order to achieve best results. Each part of the measuring instrument has to perform different duty and as such it requires different characteristics from materials. It, therefore, becomes very essential to understand the functions and duties of each part of the instrument, and also the properties and characteristics of various materials available in order to select the best choice.

The most commonly used materials for measuring instruments are described below.

Grey cast iron being easier to cast and having high compressive strength and easy to machine, is used for surface plates. Malleable cast iron being tougher and more resistant to bending and twisting is used for housings óf measuring machines. Mild steel is very suitable for headed screws with rolled threads, rivets etc. Because of its low residual magnetism it is also used for elements of magnetic circuits.

Carbon steel with 0.1 to 0.14% carbon is used for light duty gears ; with 0.4% for spindles, studs, bolts ; 0.5% for keys, shafts and parts requiring moderate wear resistance ; and with 0.75 to 1.13% for springs of various types. Carbon and carbon manganese free cutting steel is used for shaft, pivot pins, heat treated bolts etc. which require good machinability.

Low alloy steel containing 0.15% C and 0.65% Cr is used for roler bearings and various parts of measuring instruments. Some of the low alloy steels show useful properties like hardening, case hardening, creep resistance after suitable heat treatment and alloy steel containing 0.25% C, 5% Cr and 0.55% Mo is used for parts requiring high surface hardness and wear resistance. Many chrome and chrome-nickel steels are often used for small precision parts. For example such a steel with 0.22% C, 13% Cr and 0.28% S is used for bolts, nuts, screws and other precision instrument parts. Nitriding steels find wide applications where very accurate and wear prone parts are required. Stainless steel with 12 to 14% Cr is used for corrosion resistant parts.

Silver steel is used for parts subjected to wear and where long life is not obtainable with free cutting tool steel.

Oil hardening tool steel is used for slip and angle gauges.

Austenitic stainless steel being acid proof is used for membrane diaphragms. It is also used for manufacturing small springs.

Tool steel with composition of 1.1% C, 2% tungsten and 1% chromium is used for gauges.

Aluminium and its alloys find wide application for parts (like housings, indicating needles, discs, etc.) where lightness, corrosion resistance with adequate strength is the criterion. Aluminium casting alloys (with silicion which promotes die castability) are used for frames, housing, levers etc.

Brasses are highly resistant to corrosion and machined easily. These also make good bearing materials. With 28 to 35% zinc, it is used for parts to be stamped, and deep drawn. Leaded wrought brass sheets are used for lightly loaded components and are machined very easily.

Phosphor bronze is used springs, hair springs, membranes exposed to corrosive surroundings.

Nickel due to its hardness and quality of resisting corrosion is sometimes used for shafts, gears, pivot pins etc. in corrosive media.

Magensium alloys are used for light and lightly loaded components.

Zinc alloys are used for intricate parts as these can be easily die cast to obtain high accuracy and smooth finish.

Q. 1.10. (*a*) **How the error in a quantity dependent on several other quantities can be determined by the method of Binomial approximations due to errors in individual quantities.**

(*b*) **In determining an end result it is directly dependent on multiple of three measurements of three dimensions of 20 mm, 30 mm and 40 mm and each of them can be measured to an accuracy of not more than 0.1 mm. Determine the possible percentage error in the end result.**

Ans. (*a*) If a quantity Q is dependent on three other quantities q_1, q_2 and q_3 related such that

$$Q = K(q_1)^{n_1} \times (q_2)^{n_2} \times (q_2)^{n_3} \qquad (K = \text{constant})$$

then according to Binomial approximation, the errors in quantity Q will be equal to $n_1 \times$ error in $q_1 + n_2 \times$ error in $q_2 + n_3 \times$ error in q_3. It can be proved as follows :

If δq_1 is a small change in q_1, δq_2 is a small change in q_2, δq_3 is a small change in q_3, and similarly if δQ is change in Q as a result of above three, then

$$Q + \delta Q = K(q_1 + \delta\, q_1)n_2 \times (q_2 + \delta q_2)\, n_2 \times (q_3 + \delta q_3)\, n_3$$

or
$$Q + \delta Q = Kq_2^{n_1} \times q_2^{n_2} \times q_3^{n_3} \times \left(1 + \frac{\delta q_1}{q_1}\right)^{n_1} \times \left(1 + \frac{\delta q_2}{q_2}\right)^{n_2} \times \left(1 + \frac{\delta q_3}{q_3}\right)^{n_3}$$

or
$$1 + \frac{\delta Q}{Q} = \left(1 + \frac{\delta q_1}{q_1}\right)^{n_1}\left(1 + \frac{\delta q_2}{q_2}\right)^{n_2}\left(1 + \frac{\delta q_3}{q_3}\right)^{n_3}$$

If δq_1, δq_2 and δq_3 are sufficiently small, then Binomial expansion gives

$$1 + \frac{\delta Q}{Q} = 1 + n_2\left(\frac{\delta q_1}{q_1}\right) + n_2\left(\frac{\delta q_2}{q_2}\right) + n_3\left(\frac{\delta q_3}{q_3}\right)$$

or
$$\frac{\delta Q}{Q} = n_1\left(\frac{\delta q_1}{q_1}\right) = n_2\left(\frac{\delta q_2}{q_2}\right) = n_3\left(\frac{\delta q_3}{q_3}\right).$$

(*b*) In this problem

$$\frac{\delta q_1}{q_1} = \pm\frac{0.1}{20},\ \frac{\delta q_2}{q_2} = \pm\frac{0.1}{30},\ \frac{\delta q_3}{q_3} = \pm\frac{0.1}{40}$$

$$\therefore \quad \frac{\delta Q}{Q} = \pm\left(\frac{0.1}{20} + \frac{0.1}{30} + \frac{0.1}{40}\right) \times 100\% = \pm\,(0.5 + 0.33 + 0.25) = \pm\,1.08\%.$$

Q. 1.11. (*a*) **How the error in a quantity which is function of other variables can be determined by method of partial differential due to individual errors in the variables.**

(*b*) **The radius of curvature (R) of a concave surface is determined by noting two dimensions d and h such that** $\mathbf{R = \frac{d^2}{8h} + \frac{h}{2}}$.

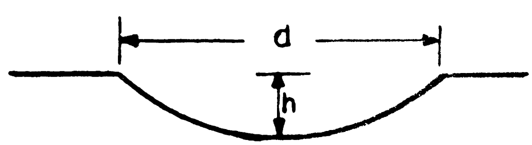


Fig. 1.40

If error in measurement of d is ± 1% and in measuring h is ± 0.5%, determine the total error in measurements of R if d = 50 mm and h = 5 mm.

Ans. (*a*) If a quantity Q is a function of variables q_1, q_2 and q_3, *i.e.* $Q = f(q_1, q_2, q_3)$ then according to method of determining error by partial differential, *i.e.* the total change in Q (or error δQ in Q) due to the small changes (or errors), δq_1, δq_2 and δq_3, in q_1, q_2 and q_3 is given by the relation.

$$\delta Q = \frac{\partial Q}{\partial q_1}\delta q_1 + \frac{\partial Q}{\partial q_2}\delta q_2 + \frac{\partial Q}{\partial q_3}\delta q_3$$

where $\frac{\partial Q}{\partial q_1}$ is the partial derivative, *i.e.* the rate of change of Q w.r.t. of q_1, keeping q_2 and q_3 constant.

Similarly, $\frac{\partial Q}{\partial Q_2}$ is the rate of change of Q w.r.t. q_2, keeping q_1 and q_3 constant and so on.

(*b*) Radius $\quad R = \frac{d^2}{\partial h} + \frac{h}{2}$

$$\therefore \quad \frac{\partial R}{\partial d} = \frac{1}{8h} \times (2d) + 0 = \frac{2d}{8h} = \frac{d}{4h}$$

and
$$\frac{\partial R}{\partial h} = \frac{d^2}{8}(-1 \times h^{-2}) + \frac{1}{2} = -\frac{d^2}{8h^2} + \frac{1}{2}$$

$$\delta R = \frac{d}{4h} \times \delta d + \left(-\frac{d^2}{8h^2} + \frac{1}{2}\right) \times \delta h$$

$$= \frac{d}{4h}\left(\pm \frac{d}{100}\right) + \left(-\frac{d^2}{8h^2} + \frac{1}{2}\right)\left(\pm \frac{h}{200}\right) = \pm\left(\frac{d^2}{400h} - \frac{d^2}{1600h} + \frac{h}{400}\right)$$

$$= \pm\left(\frac{50 \times 50}{400 \times 5} + \frac{50 \times 50}{1600 \times 5} + \frac{5}{400}\right) = \pm (1.25 + 0.31 + 0.01) = \pm 1.57\%.$$

Q. 1.12. (*a*) **How the error in a quantity dependent on several other quantities can be determined by the method of logarithmic differentiation due to errors in individual quantities ?**

(*b*) **Determine the resultant error in angle θ determined by a sine bar by measuring height of slip gauge and the length between rollers of sine bar such that $\sin \theta = \frac{h}{l}$.**

Ans. (*a*) If a quantity Q is dependent on three other variables q_1, q_2 and q_3 related such that $Q = K q_1^{n_1} q_2^{n_2} q_3^{n_3}$ (K = constant) then $\log_e Q = \log_e K + n_1 \log_e q_1 + n_2 \log_e q_2 + n_3 \log_e q_3$ and differentiating it,

$$\frac{dQ}{Q} = n_1 \frac{dq_1}{q_1} + n_2 \frac{dq_2}{q_2} + n_3 \frac{dq_3}{q_3}$$

If small finite changes δq_1, δq_2 and δq_3 occur, then

$$\frac{\delta Q}{Q} = n_1 \frac{\delta q_1}{q_1} + n_2 \frac{\delta q_2}{q_2} + n_3 \frac{\delta q_3}{q_3}$$

which gives same result as in problem 1.11 above.

(*b*) $\sin \theta = \frac{h}{l}$, taking logs

$$\log_e (\sin \theta) = \log_e h - \log_e l$$

Differentiating, we have $\frac{\cos \theta}{\sin \theta} d\theta = \frac{dh}{h} - \frac{dl}{l}$

$$d\theta = \left(\frac{dh}{h} - \frac{dl}{l}\right) \tan \theta$$

or
$$= \left(\frac{dh}{h} - \frac{dl}{l}\right) \frac{h}{\sqrt{l^2 - h^2}} = \left(dh - h\frac{dl}{l}\right) \Big/ \sqrt{l^2 - h^2}$$

For small finite errors δh and δl, the error in θ is $\delta\theta = +\left(\delta h + h\frac{\delta l}{l}\right) \Big/ \sqrt{l^2 - h^2}$.

Q. 1.13. A dial indicator has a scale from zero to 1 mm over an arc of 270° and 100 divisions on scale ; the radius of scale line being 30 mm. During a calibration test, the following values were observed :

Calibration length (mm)	Scale value (mm)	Calibration length (mm)	Scale value (mm)
0.00	0.00	0.60	0.59
0.10	0.10	0.70	0.70
0.20	0.19	0.80	0.81
0.30	0.29	0.90	0.91
0.40	0.41	1.00	1.00
0.50	0.50		

(*a*) **Determine the sensitivity.**

(*b*) **Determine the maximum error as** (*i*) **percentage of scale value,** (*ii*) **percentage of full scale (fiducial) value.**

(*c*) **Determine whether the indicator conforms to the maker's specification of accuracy of within ± 1.0% of full scale deflection.**

Ans. (*a*) Sensitivity $= \dfrac{\text{Range}}{\text{No. of divisions}} = \dfrac{1}{100} = 0.01$ mm

(*b*) (*i*) From third column, maximum error as percentage of scale value is + 5%, – 2.5% ;

(*ii*) and from fourth column, maximum error as percentage of full scale value = ± 1%

(*c*) Yes

Calibration length lc *(mm)*	*Scale value* ls *(mm)*	*Error as % of scale value* $\dfrac{lc - ls}{lc}\%$	*Error as % of full scale value* $\dfrac{lc - ls}{lc_{max}}\%$
0.00	0.00	0	0
0.10	0.10	0	0
0.20	0.19	+ 5	+ 1
0.30	0.29	+ 3.3	+ 1
0.40	0.41	– 2.5	– 1
0.50	0.50	0	0
0.60	0.59	+ 1.7	+ 1
0.70	0.70	0	0
0.80	0.81	– 1.25	– 1
0.90	0.91	–1.1	– 1
1.00	1.00	0	0

Q. 1.14. A parameter 'R' is a function of 3 independent parameters 'A', 'B' and 'C'. The five readings of parameters A, B and C respectively are

A—100.01, 100, 99.98, 99.99 and 100.0.2 ;

B—20.01, 20.02, 19.98, 19.99, 20.00 ;

C—5.00, 5.01, 5.02, 4.98, 4.99.

The values of uncertainty in calibration of A, B and C are stated as 0.02%, 0.01%, and 0.005% respectively. Determine random uncertainty, systematic uncertainty and overall uncertainty in determination of value of 'R' for 95% confidence level. Take value of t for sample of 5 and 95% confidence level as 2.78 and value of K as 1.96.

Ans. For parameter A, mean $= \dfrac{100.01 + 100 + 99.98 + 99.99 + 100.02}{5}$

Sample standard deviation $S_A = \sqrt{\dfrac{.01^2 + 0^2 + .02^2 + 0.1^2 + 0.2^2}{5}} = .01\sqrt{\dfrac{10}{5}} = .01 \times 1.41$

Random uncertainty in parameter A

$$\mu_{rA} = t\frac{S_A}{\sqrt{n-1}} = \frac{2.78 \times .01 \times 1.41}{\sqrt{5-1}} = 1.96 \times 10^{-2}$$

Similarly U_{rB} and U_{rC} are also 1.96×10^{-2}

Random uncertainty of $R = 10^{-2}\sqrt{1.96^2 + 1.96^2 + 1.96^2} \times R$

and percentage value $= 3.45 \times 10^{-2}\%$

Systematic uncertainty

$$U_s = K\sqrt{\frac{0.2^2 + 0.01^2 + 0.005^2}{3}} = 1.96 \times 0.01\sqrt{\frac{4+1+.25}{3}}$$

$$= 1.96 \times 0.01\sqrt{1.75} = 1.96 \times 1.32 \times 0.01 \approx 2.59 \times 10^{-2}$$

Overall uncertainty $= \sqrt{U_R^2 + U_S^2} = 10^{-2}\sqrt{3.45^2 + 2.59^2} = 4.3 \times 10^{-2}\%$.

Q. 1.15. Give examples for following methods of measurement :

(*a*) **Direct** (*b*) **Indirect**
(*c*) **Fundamental** (*d*) **Comparison**
(*e*) **Direct comparison** (*f*) **Substitution**
(*g*) **Transposition** (*h*) **Differential**
(*i*) **Coincidence** (*j*) **Null**
(*k*) **Deflection** (*l*) **Interpolation**
(*m*) **Extrapolation** (*n*) **Complementary**
(*o*) **Resonance.**

Ans. (*a*) Direct method of measurement—Measurement of a mass on equal-arm balance ; and measurement of length by means of graduated scale.

(*b*) Indirect method of measurement—Measurement of speed on the basis of measurement of distance and time, and measurement of density of a body on the basis of measurements of its mass and dimensions.

(*c*) Fundamental method of measurement—Measurement of pressure with the aid of U-tube manometer by which the pressure is deducted from measurements of density, acceleration due to gravity and length, which in turn are measured based on the base quantities of length, mass and time.

(*d*) Comparison method of measurement—Measurement of pressure by Bourdon-tube gauge, and measurement of volume of liquid by means of a material of capacity.

(*e*) Direct comparison method of measurement—Measurement of length by means of a graduated rule ; and measurement of volume of liquid by means of a material measure of capacity.

(*f*) Substitution method of measurement—Determination of temperature with a Beckmann thermometer by reproducing the same indication by means of a known temperature.

(*g*) Transposition method of measurement—Determination of a mass by means of a balance and known weights, using the Gauss double-weighing method.

(*h*) Differential method of measurement—Determination of length by a comparator.

(*i*) Coincidence method of measurement—Measurement of length by vernier caliper.

(*j*) Null method of measurement—Measurement of an electrical resistance by means of wheatstone bridge and null indicator.

(*k*) Deflection method of measurement—Measurement of mass by spring balance ; and Measurement of length by dial indicator.

(*l*) Interpolation method of measurement—Linear interpolation between scale marks on a scale.

(*m*) Extrapolation method of measurement—establishment on the IPTS (International Practical Temperature Scale) of temperature above the highest established fixed point.

(*n*) Complementary method of measurement—Determination of the volume of a solid by liquid displacement.

(*o*) Resonance method of measurement—Measurement of frequencies by means of a sonometer or a vibrating-reed frequency meter.

Q. 1.16. Differentiate between indicating instrument, recording instrument, totalising instrument, integrating instrument, analogue/digital instruments, moving scale/moving index measuring instruments.

Ans. Indicating instrument is a measuring which displays the value of a measured or a related value. It is intended to give, by means of a single unique observation, the value of the measured quantity at the time of that observation.

A recording instrument provides a record of the value of measurand. The record may be permanent or semi-permanent from which the values of measured quantity can be obtained.

A totalising instrument is one which determines the value of a measurand by summation of partial values of the measurand obtained simultaneously or consecutively from one or more sources. For example, electrical power-summation meter ; discontinuous dispenser of liquid fuel with one or more measuring capacities.

An integrating instrument is one which determines the value of a measurand by integrating a quantity with respect to another quantity. For example, planimeter, continuous-belt-weighing machine.

Analogue instrument is one in which the output or display is a continuous function of the corresponding value of the measurand (pointer type of instrument) but a digital instrument has no pointer and it converts the quantity to be measured into coded discrete signals and provides a digitised output.

In moving scale measuring instrument, indications are given by the position of a moving scale in relation to a fixed index ; and in a moving index measuring instrument, indications are given by position of a moving index in relation to a fixed scale.

Q. 1.17. What is the difference between differential method of measurement and null method of measurement ?

Ans. Differential method of measurement is the method of measurement in which the measurand is compared with a quantity of the same kind,of known value only slightly different from the value of the measurand, and in which the difference between the two values is measured, *e.g.*, measurement using comparators.

Null method of measurement is the method of measurement in which the value of the measurand is determined by balancing, adjusting one or more quantities, of known values, to which the measurand has a known relationship at balance.

Q. 1.18. What is the difference between correction and correction factor ?

Ans. Correction is a value which when added algebraically to the uncorrected result of measurement, compensates for an assumed systematic error. Correction factor is the numerical factor by which the uncorrected result of a measurement is multiplied to compensate for an assumed systematic error.

Q. 1.19. What is the difference between the repeatability of measurements and the reproducibility of measurements ?

Ans. Repeatability of measurements is the quantitative expression of the closeness of the agreement between the results of successive measurements of the same measurand carried out subject to the conditions that no change is made in the method of measurement, observer, measuring instrument, location, conditions of use, and that the experiment is repeated over a short period of time. It may be expressed quantitatively in terms of the dispersion of the results.

Reproducibility of measurements is the quantitative measure of the closeness of the agreement between the results of measurements of the same measurand, where the individual measurements are carried out by changing the method of measurement, observer, measuring instrument, location, conditions of use, time etc. It may also be expressed quantitatively in terms of the dispersion of the results.

Q. 1.20. What is the difference between relative error, random error and systematic error ?

Ans. Relative error is the absolute error of measurement divided by the conventional true value of the measurand.

Random error is a component of the error of measurement which, in the course of a number of measurements of the same measurand, varies in an unpredictable manner. This error can't be corrected.

Systematic error is a component of the error of measurement which, in the course of a number of measurements of the same measurand, remains constant or varies in a predictable way.

Q. 1.21. Explain the difference between random errors and systematic errors.

Ans. Certain errors are inherent in any process of measurement. Errors which vary in an unpredictable manner both in magnitude and sign, following a normal distribution about a mean value, are referred to as random errors. Such errors may be due to uncontrollable environmental condition, personal judgement of the observer, and inherent instability of the measuring instrument. The normal distribution becomes clear when large number of readings are taken under controlled conditions. However for smaller number of observations, statistical results based on normal distribution need to be corrected by means of student's '*t*' factor.

Errors due to system which can't be reduced by taking large number of observations are referred to as systematic errors. These occur due to inability in detection of measuring system, errors in standards, constant bias, etc. These may either be constant in magnitude or variable (but only in one direction). These (constant) do not change with time and can be taken care of by zero setting. Those errors which vary with the magnitude of measured quantity can be taken care of by calibration. Variable errors are function of time (because of ageing effect.)

Q. 1.22. Fill in the blanks ?

1. .... is the field of knowledge dealing with the problems of measurements.

2. The operations conducted with a view to verify that the measuring instrument conforms to a standard is called .... instrument.

3. Partial examination of a measuring instrument whose final verification is done at the place of installation is called .... examination.

4. Set of operations carried out with regard to verifying the statutory provisions like inscriptions, dimensions, locations of stamps, etc. is known as .... examination.

5. The examination of a measuring instrument with the object of ensuring that the stamp is valid, at the instrument has not been subjected to any modification after verification, and that its errors do not exceed the maximum errors permitted in use is known as .... examination.

6. A set of experimental operations carried out with the object of determining the value of a quantity is called ....

7. The physical phenomenon which is the foundation of measurement is called the .... of measurement.

8. The sequence of operations necessary for the execution of a measurement is called the .... of measurement.

9. The set of operations having the object of ensuring that the measuring instrument satisfies the statutory provisions in relation to its metrological qualities is called .... examination.

10. The operation consisting of obtaining the indication of the measuring instrument is called ....

11. The value of the measured quantity obtained by a measurement is called .... of measurement.

12. Standards reduce diversity to a reasonable level and provide .... parts.

13. .... is the factor by which the indication of the instrument is multiplied to obtain the result of measurement.

14. The susceptibility of a measuring device to having its indications converted to a meaningful number is called ....

15. .... implies the ease with which observations can be made accurately.

16. The output signal from many measuring instruments need to be amplified so as to be .... In optical magnification, if the mirror is tilted by angle θ, the reflected lights gets displaced by angle ....

17. .... designates the degree of agreement of the measured size with its true magnitude as expressed in standard units of measurements.

18. .... expresses the degree of repeatability of the measuring process.

19. The capability of a measuring instrument to detect and to faithfully indicate even small variations of the measured dimension from nominal size of part is called ....

20. .... is the designation of the instrument's capability for consistent indications and is often expressed as the maximum drift over the specific time.

21. The .... of dimensional measurements may be regarded as a function of the occurring errors and of their assessment.

22. The maximum limit of size of an external dimension or the maximum limit of size of an internal dimension is referred to as ....

23. .... errors are primarily, yet not exclusively, associated with the human element and are considered as resulting from inaccurate scale reading, improper specimen staging, mistakes in recording, etc.

24. .... errors can neither be predicted nor eliminated, their probable magnitude and relative frequency are evaluated statistically for establishing the probable precision of the measuring process.

25. The concept of .... as a measure of the range of scatter in the measured values from a mean is applied for qualifying the precision of the instrument.

26. .... errors are those associated, with the measuring instrument's capabilities, environment and other extraneous conditions, which are generally controllable or, at least, measurable.

27. The verification of the measuring instrument's indicting accuracy, both in its original state and during usage at appropriate intervals, is accomplished by means of properly devised and implemented .... processes.

28. When the process requirements of the gauging are adequately assured, it is the .... of the instrument which will primarily determine the reliability of the measurements.

29. As a general rule, the measuring instrument's consistent indicating accuracy should be .... than the smallest graduation of the readout element.

30. .... is a comparison process whereby an unknown quantity is compared with a known quantity or standard.

31. The process of comparing one measuring device against a higher-order standard of greater accuracy is known as ....

32. The concept of .... has to be followed to ensure that all measurements are consistent.

33. .... refers to the minimum change in value that the instrument can reliability indicate.

34. The functions of .... are to control the dimensions of a product within the prescribed limitations and to segregate/reject a product that is outside those limitations.

35. Gauging by .... through the use of fixed gauges is a rapid method of determining whether or not a product is within prescribed limits.

36. Gauging by .... provides a means of evaluating the size of each part, establishing its relationship to limits of size, and determining to what extent limits of size are exceeded by rejected parts.

37. Gauging by attributes is accomplished by use of .... and gauging by variables by the use of ....

38. An attribute of a phenomenon, body or substance, which may be distinguished qualitatively and determined quantitatively is called ....

39. The quantity conventionally accepted as independent of other quantities in a system is called .... quantity but a quantity which is a function of base quantities of a system is called .... quantity.

40. The set of operations having the object of determining the value of a quantity is called ....

41. The set of theoretical and practical operations, in general terms, involved in the performance of measurements according to a given principle is called ....

42. An estimate characterising the range of values within which the trial value of a measurand lies is called .... measurement.

43. The portion of the scale over which the instrument purports to comply with specified limits of error is called .... range.

44. The concept of establishing a valid calibration of a measuring instrument or measurement standard, by step-by-step comparison with better standards up to an accepted or specified standard is called ....

45. The smallest change in the quantity measured which produces a perceptible movement of the index is called ....

46. The process of determining the characteristic relation between the values of the physical quantity applied to the instrument and the corresponding positions of the index is called ....

47. The property which characterises the ability of a measuring instrument to respond to small changes of the quantity measured is called ....

48. A curve which expresses the correspondence between the values of the quantity measured and the values indicated by the instrument is called ....

49. The algebraic difference between the upper and lower values specified as limiting range of operation of a measuring instrument is called ....

50. The reciprocal of gain where the gain is less than unity is called ....

51. Instruments in which the index is not in the same plane as the scale are subject to .... errors.

52. The progressive reduction or suppression of the free oscillations of a measuring instrument is called ....

53. The property of a measuring instrument whereby it gives different indications, or responses, for the same value of the measured quantity, according to whether that value has been

reached by a continuously increasing change or by a continuously decreasing change of that quantity is called ....

54. That part of the instrument error whereby a change of the indication, or response, departs from proportionality to the corresponding change of the value of the measured quantity over a defined range is called ....

55. The error which may result from the measurement of the value of a quantity, by a process which converts the quantity into a digital indication, or response is called ....

56. The quality which characterises the ability of a measuring instrument to give indentical indications for repeated applications of the same value of the measured quantity under stated conditions of use is called ....

57. Determination of a mass by means of a balance and known masses using the Borda substitution method is the example of .... measurement.

58. A method of measurement of a quantity in accordance with a definition of the unit of that quantity is called .... method of measurement.

59. A method of measurement in which the measurand is compared directly with a quantity of the same kind having a known value is called .... method of measurement.

60. A method of measurement in which the measurand is replaced by a quantity of the same kind, of known value, and chosen so that the effects on the indicating device are the same is called .... method of measurement.

61. All the operations for the purpose of determining the values of the errors of a measuring instrument are called ....

62. Human error of observation and judgement can be avoided by switching over to ....

Q. 1.23. Provide a single word for the following ?

(*a*) Science of precision measurement of length and angles and other quantities which can be expressed in terms of linear or angular units.

(*b*) Method of measurement in which the result is good or bad, accepted or rejected.

(*c*) Smallest change in the measured quantity which produces a perceptible movement of the index.

(*d*) Whether the pointer in instrument is just moving or just not moving.

(*e*) Extent to which the instrument repeats its results when making repeat measurements on the same unit.

(*f*) The measure of the scatter of measurement values of a given dimension by same instrument.

(*g*) Technique of measuring small variations of a continuous nature.

(*h*) The extent to which the average of a series of repeat measurements made by the instrument on a single dimension differs from the true value.

(*i*) Algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument.

(*j*) The property which characteristics the ability of a measuring instrument to maintain constant certain specified metrological properties.

(*k*) A reading error which is produced when the index being at a certain distance from the surface of the scale, the observation of the reading is not made in the appropriate direction.

(*l*) The mathematical function expressing the relationship between a stimulus and the corresponding response over a defined range of conditions.

(*m*) The relationship of the change of the response to the corresponding change of the stimulus.

(*n*) The error of a measuring instrument when used under reference conditions.

(*o*) A curve which expresses the correspondence between the values of the quantity measured and the values indicated by the instrument.

(*p*) The range through which a stimulus may be varied without indicating a change in response.

(*q*) The error which results from the dispersion of the indications of a measuring instrument under stated conditions of use.

(*r*) The discrepancy between the result of the measurement and the true value of the quantity measured.

(*s*) An error which varies in an unpredictable manner (both in magnitude and sign), when a large number of measurements of the same value of a quantity are made under effectively identical conditions.

(*t*) All the operations for the purpose of determining the values of the efforts of a measuring instrument.

(*u*) The operations having the object of determining the value of quantity.

(*v*) The value of a quantity conventionally accepted as having a numerical value equal to 1.

(*w*) A device which responds to the presence of particular quantity without necessarily measuring the value of that quantity.

(*x*) The divergence of the value of a quantity from a standard or reference value.

(*y*) Algebraic sum of the systematic errors affecting the indications of a measuring instrument under defined conditions of use.

(*z*) The interval between the lower and upper range limits.

Q. 1.24. Unit of measurement is the value of a quantity conventionally approved as having a numerical value equal to one.

Match the following two parts in connection with unit of measurement.

Part A	*Part B*
1. The conventional symbol designating the unit of measurement.	(*a*) Supplementary units
2. The unit of measurement, the use of which is imposed or allowed by a law of the state	(*b*) Coherent system of units of measurement
3. Unit of measurement of one of the base quantities.	(*c*) Coherent units
4. Unit of measurement of a derived quantity	(*d*) Legal unit of measurement
5. Unit of measurement which is expressed with the help of base units by a formula, the numerical coefficient of which is equal to 1.	(*e*) System of units of measurement
6. A set of base and derived units, relating to a particular system of quantities like CGS, MKS, SI, etc.	(*f*) International system of units
7. Measures for plane and spheroidal angles.	(*g*) Symbol of unit of measurement
8. Unit of measurement which is multiple (submultiple) of the unit and which is formed in accordance with the grading principle approved for the corresponding unit.	(*h*) Unit of measurement outside the system
9. A system of units of measurement composed of a set of base units and coherent derived units.	(*i*) Coherent unit of measurement

10. Unit of measurement which does not belong to the system of units of measurement envisaged.	(*j*) Base unit of measurement
11. System of units established by the General Conference of Weights and Measures.	(*k*) Multiple of unit of measurement
12. Same system and unit of measurement are used regardless of industry, trade or discipline.	(*l*) Derived unit of measurement

Q. 1.25. Quantity is the attribute of a phenomenon or of a body which is capable of being distinguished qualitatively and determined quantitatively, e.g. diameter of a shaft. Match the following two parts in relation to "quantity"

Part A	*Part B*
1. A quantity subjected to a measurement.	(*a*) scale of a quantity
2. A quantity which is not the subject of measurement but which influences the values of the quantity to be measured.	(*b*) Local value of a quantity
3. The value which characterises a quantity determined perfectly in the conditions which exist at the moment when that value is observed.	(*c*) Derived quantity
4. Pure number in the expression of a value of the specified quantity.	(*d*) Value of a specified quantity
5. The Value of a quantity measured at a place or a specified point in space.	(*e*) Base quantity
6. A set which comprises of a given group of base quantity and the corresponding derived quantities.	(*f*) Dimension of a quantity
7. The designation of quantities which in a system of quantities are accepted as being independent of one another and by means of which the quantities derived from them in that system may be expressed by equation of definitions.	(*g*) Influence quantity
8. The quantity defined in a system of quantities as being a function of the base quantities of that system.	(*h*) Numerical value of a quantity
9. The expression which represents a quantity of a system, as a product of the powers of the base quantities of that system, with a numerical coefficient equal to 1.	(*i*) Dimensionless quantity
10. A quantity which does not depend on any of the base quantities of the given system of quantities (like angle)	(*j*) System of a quantity
11. The set of values of quantity, determined in accordance with prescriptions and accepted by convention	(*k*) True value of quantity

12. The quantity expressed as the product of a number and the unit of measurement.	(*l*) Quantity to be measured

Q. 1.26. Verification involves a set of operations carried out with the objective of establishing and conforming that the measuring instrument fully satisfies the statutory provisions. It includes examination and stamping.

Match the following two parts concerning verification.

Part A	*Part B*
1. Verification of a homogeneous batch of measuring instruments on the basis of the results of examination of one or more specimens from that batch.	(*a*) Renewal of verification
2. Verification of a new measuring instrument not verified earlier.	(*b*) Full verification
3. Verifications after initial verification (like statutory periodical verification after repairs or before expiry of the period of validity, etc.)	(*c*) Periodical verification
4. Extension of the validity of verification of measuring instrument without a fresh examination (in case where that instrument has remained unused after verification).	(*d*) Initial verification
5. Subsequent verification of a measuring instrument for which a full examination of the instrument as for initial verification is necessary.	(*e*) Obligatory verification
6. Subsequent verification of a measuring instrument for which simplified examination is permitted.	(*f*) Exceptional verification
7. Verification carried out periodically at intervals of time and according to the methods established by regulations.	(*g*) Optional verification
8. Verification of a measuring instrument carried out for exceptional reasons.	(*h*) Verification by sampling
9. Verification to be carried out so that the use of measuring instrument is not prohibited.	(*i*) Loss of validity of verification
10. Non compulsory verification of a measuring instrument.	(*j*) Presentation for verification
11. Set of operations (administrative or physical) to be carried out by a person who presents a measuring instrument for verification.	(*k*) Simplified verification
12. Cancellation of the fact of validity of verification of a measuring instrument when it no longer conforms to the statutory provisions.	(*l*) Subsequent verification

Q. 1.27. Match the following two parts in connection with the methods of measurement.

Part A	*Part B*
1. Method of measurement in which the value of a quantity is obtained from measurements carried out by direct method of measurement of other quantities, connected with the quantity to be measured by a known relationship.	(*a*) Method of measurement without contact
2. Method of measurement based on the measurements of based quantities entering into the definition of the quantity.	(*b*) Method of measurement by extrapolation
3. Method of measurement based on comparison of the value of a quantity to be measured with a known value of the same quantity or a known value of another quantity, which is a function of the quantity to be measured.	(*c*) Method of differential measurement
4. Method of measurement by direct comparison in which the value of a quantity to be measured is replaced by a known value of the same quantity, so selected that the effects produced in the indicating device by these two values are the same.	(*d*) Method of measurement by deflection
5. Method of measurement by comparison, based on the comparison of the quantity to be measured with a quantity of the same kind, with a value known to be slightly different from that of the quantity to be measured, and the measurement of the difference between the values of these two quantities.	(*e*) Method of measurement by interpolation
6. Method of differential measurement in which the difference between the value of the quantity to be measured and the known value of the same quantity with which it is compared, is brought to zero.	(*f*) Method of fundamental measurement
7. Method of differential measurement in which a very small difference between the value of the quantity to be measured and the known value of the same kind with which it is compared, is determined by an observation of the coincidence of certain lines, or signals.	(*g*) Method of measurement by substitution
8. Method of measurement by comparison in which the value of the quantity measured is determined by the deflection of an indicating device.	(*h*) Method of measurement by complement

9. Method of measurement in which the value of the quantity to be measured is compared by a known value of the same quantity, selected in such a manner that the sum of these two values is equal to a certain value of comparison fixed in advance.	(*i*) Method of measurement by coincidence
10. Method of measurement consisting of determining the value of the quantity measured on the basis of the law of correspondence and known values of the same quantity, the value to be determined lying between two known values.	(*j*) Method of measurement by comparison
11. Method of measurement consisting of determining the value of the quantity measured on the basis of the law of correspondence and known values of the same quantity, the value to be determined lying outside the known values.	(*k*) Method of null measurement
12. Method of measurement in which the sensor is not placed in contact with the object whose characteristics are being determined.	(*l*) Method of indirect measurement.

Q. 1.28. Match the parts A and B in regard to standards of measurements ?

Part A	*Part B*
1. Working standards used for setting diameter measuring machines.	(*a*) Interferometric
2. Slip gauge placed between the three balls mounted in a chuck on the tailstock and a single ball mounted on the measuring unit which is mounted on the main body of the machine by two steel strips.	(*b*) Reference discs
3. The technique by which the value of any measurement can be related in discrete steps and with known error to the value of the concerned national standard.	(*c*) Points of Bessel
4. If l is the length of bar, its supports placed $0.577\, l$ apart so that ends of bar lie in horizontal plane.	(*d*) Precision polygons
5. If l is the length of bar, its supports at $0.54\, l$ apart to give minimum deflection.	(*e*) Length standard
6. Concerned with angular standard.	(*f*) Slip gauges
7. Distance between the centres of engraved lines.	(*g*) Supplementary SI unit
8. Herts, newton, watt, joule. etc.	(*h*) Unit of time, second
9. One of the methods for calibration of slip gauges.	(*i*) Derived SI unit
10. End standards.	(*j*) Eden rolt comparator

11. The duration of 9192631770 period of the radiation corresponding to the transition between the two hyper fine levels of the ground state of the cesium 133 atom.	(*k*) Airy points
12. Radian and steradian.	(*l*) Traceability

Q. 1.29. Match the following two parts in connection with measuring instruments.

Part A	*Part B*
1. A measuring device which serves to transform and provides an output quantity having a given established relationship to the input quantity.	(*a*) Scale
2. The element of a measuring instrument to which a measurand is directly applied.	(*b*) analogue measuring instrument
3. The fixed or movable part of an indicating device (*e.g.* a pointer, luminous spot, liquid surface, etc.) whose position with reference to the scale marks enables an indicated value to be observed.	(*c*) adjustment
4. An ordered set of scale marks, together with any associated numbering, forming a part of an indicating device.	(*d*) scale interval
5. A device or substance which indicates the presence of a particular quantity without necessarily measuring the value of that quantity (like gold-leaf electroscope, temperature sensitive paint).	(*e*) indicating device
6. A measuring instrument in which the output or display is a continuous function of the value of the measurand	(*f*) dial
7. The set of components in a measuring instrument which displays the value of a measurand.	(*g*) expanded scale
8. The operation intended to bring a measuring instrument into a state of performance and freedom from bias suitable for its use.	(*h*) sensor
9. A scale of measuring instrument in which part of the scale range occupies a disproportionately large part of the scale length.	(*i*) scale division
10. The difference between the scale values corresponding to two successive scale marks.	(*j*) index
11. The part of a scale between any two successive scale marks.	(*k*) detector
12. The part of an indicating device, fixed or moving, which carries the scale (s).	(*l*) measuring transducer.

Q. 1.30. Match the parts A and B regarding types of errors of measuring instruments.

Part A	Part B
1. Difference between indication of a measuring instrument and true value of measurand.	(*a*) intrinsic error
2. Error at a specified value chosen for checking instrument	(*b*) tracking error
3. Initial error corresponding to zero value of the measurand	(*c*) datum error
4. Error of a measuring instrument used under reference conditions	(*d*) bias error
5. algebraic sum of the systematic errors affecting the indications of a measuring instrument under defined conditions of use	(*e*) relative error
6. the error which results from the dispersion of the indications of a measuring instrument under stated conditions of use	(*f*) systematic error
7. error of measuring instrument divided by a value specified for the instrument (like span, or upper limit of nominal range)	(*g*) zero error
8. error arising from a lag in the response of a measuring instrument to a changing stimulus	(*h*) scatter/dispersion
9. the slow variation with time of a metrological characteristic of a measuring instrument	(*i*) fiducial error
10. absolute error divided by true value	(*j*) error
11. the phenomenon exhibited by a measuring instrument whereby it gives different indications in a series of measurements of the same value of the quantity measured	(*k*) drift
12. error which varies in a predictable way	(*l*) repeatability error

Q. 1.31. Match the following two parts in connection with the important characteristics of measuring instrument ?

Part A	Part B
1. change in the respone of a measuring instrument divided by the corresponding change in the stimulus	(*a*) dead band
2. the range through which a stimulus can be varied without producing a change in the response of a measuring instrument	(*b*) drift
3. the property of a measuring instrument whereby its response to a given stimulus depends on the sequence of preceding stimuli	(*c*) resolution
4. the ability of a measuring instrument not to affect the value of the measurand	(*d*) sensitivity

5. ability to give indications approaching the true value of a measurand	(e) discrimination
6. slow variation with time of a metrological characteristic of a measuring instrument	(f) response time
7. a quantitative expression of the ability of an indicating device to distinguish meaningfully between closely adjacent value of the quantity indicated.	(g) accuracy
8. the ability of a measuring instrument to respond to small changes in the value of stimulus	(h) hysteresis
9. the modulus of the difference between the two limits of a nominal range of a measuring instrument	(i) instrument constant
10. the coefficient by which a direct indication must be multiplied to obtain the indication	(j) span
11. time interval between the instant an instrument is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits of its final steady value	(k) specified measuring range
12. the set values of a measuring instrument is intended to lie within specified limits.	(l) transparency

Q. 1.32. To which areas, legal metrology applies ?

Ans. Legal metrology applies mainly to the following areas :

(*i*) **Trade**—retail trade where consumer protection is of prime importance, and also wholesale and international trade.

(*ii*) **Health**—need to ensure credible measurement results from instruments and methods used in medical diagnosis and care.

(*iii*) **Safety**—speed of vehicles, light and noise levels at the place of work.

(*iv*) **Environmental protection**—need for accurate and credible measurements to tackle pollution.

(*v*) **Official controls**—sound metrological rules in the establishment of taxes and surveying, etc.

(*vi*) **Economic and social development**—to accurately determine the value of the products and services imported/exported through quantitative and qualitative measurements.

Q. 1.33. There is increasing demand for international uniformity of measurements. Elaborate this statement.

Ans. International uniformity of measurements is based on standards held by national metrological institutes and this being extended throughout countries by accredited laboratories and national calibration chains. To be practical several intercomparisons need to be organised for the same unit, and all results be linked to a single common reference. This leads to set up a hierarchical structure of the key comparisons. The attached uncertainty will have to take into account the uncertainty of transfer of the key comparison reference value by the link laboratories.

Q. 1.34. Traceability is a desired characteristic of every measurement. Define traceability.

Ans. Traceability is defined as the property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. Traceability is very closely linked with the concept of uncertainty.

A pyramid is often used to illustrate traceability ; the pyramid's apex showing the beginning of traceability chain with SI units maintained by the BIPM (Bureau International des Poids et Measures). The pyramid extends to national standards maintained by the national metrology institutes (NMI) in each country, to regional standards, to working standards, and ultimately to measurements made by end users.

Q. 1.35. Globalisation of trade calls for reduction of all kinds of barriers and mutual recognition agreements. Elaborate this statement.

Ans. It is not only enough to establish a certain level of equivalence between national standards of several countries, but same must be recognised by the partners in the world trade to enable global trade to take place smoothly. Thus there has to be mutual recognition of measurement standards and calibration certificates issued by National Metrology Institutes and the laboratories attached to them. NMIs should evolve some sort of quality system so that calibration certificates issued by other participating institutes can be recognised as part of global trade.

ANSWERS

Ans. to Q. 1.22.

1. *Metrology* 2. *examination* 3. *preliminary* 4. *external administrative* 5. *supervisory* 6. *measurement* 7. *principle* 8. *process* 9. *metroloigcal* 10. *observation* 11. *result* 12. *interchangeable* 13. *constant* 14. *readability* 15. *readability* 16. *readable, 2 θ* 17. *accuracy* 18. *precision* 19. *sensitivity* 20. *stability* 21. *reliability* 22. *maximum material limit* 23. *Random* 24. *random* 25. *Standard deviation* 26. *Systematic* 27. *calibration* 28. *capability* 29. *better* 30. *Measurement* 31. *calibration* 32. *traceability* 33. *sensitivity* 34. *gauging* 35. *attributes* 36. *variables* 37. *limit gauges, indicating gauges* 38. *measurable quantity* 39. *base, derived* 40. *measurement* 41. *method of measurement* 42. *uncertainty* 43. *effective* 44. *traceability* 45. *discrimination* 46. *calibration* 47. *discrimination* 48. *calibration* 49. *span* 50. *attenuation* 51. *parallax* 52. *damping* 53. *hysteresis* 54. *non-linearily error* 55. *quantisation error* 56. *repeatability* 57. *substitution* 58. *definitive* 59. *direct-comparison* 60. *substitution* 61. *calibration* 62. *digital readouts.*

Ans. to 1.23.

(*a*) *Engineering Metrology* (*b*) *attribute* (*c*) *discrimination* (*d*) *threshold effect* (*e*) *precision* (*f*) *standard deviation* (*g*) *dynamic metrology* (*h*) *accuracy* (*i*) *span* (*j*) *stability* (*k*) *parallax error* (*l*) *transfer function* (*m*) *sensitivity* (*n*) *instrinsic error* (*o*) *calibration curve* (*p*) *dead band* (*q*) *repeatability error* (*r*) *error* (*s*) *random error* (*t*) *calibration* (*u*) *measurement* (*v*) *unit* (*w*) *detector* (*x*) *deviation* (*y*) *bias error* (*z*) *range*

Ans. to Q. 1.24. : 1—*g*, 2—*d*, 3—*j*, 4—*l*, 5—*i*, 6—*j*, 7—*a*, 8—*k*, 9—*b*, 10—*h*, 11—*f*, 12—*c*.

Ans. to Q. 1.25. : 1—*l*, 2—*g*, 3—*k*, 4—*h*, 5—*b*, 6—*j*, 7—*e*, 8—*c*, 9—*f*, 10—*i*, 11—*a*, 12—*d*.

Ans. to Q. 1.26. : 1—*h*, 2—*d*, 3—*l*, 4—*a*, 5—*b*, 6—*k*, 7—*c*, 8—*f*, 9—*e*, 10—*g*, 11—*j*, 12—*i*.

Ans. to Q. 1.27. : 1—*l*, 2—*f*, 3—*j*, 4—*g*, 5—*c*, 6—*k*, 7—*i*, 8—*d*, 9—*h*, 10—*c*, 11—*b*, 12—*a*.

Ans. to Q. 1.28. : 1—*b*, 2—*j*, 3—*l*, 4—*k*, 5—*c*, 6—*d*, 7—*e* 8—*i*, 9—*a*, 10—*f*, 11—*h*, 12—*g*.

Ans. to Q. 1.29. : 1—*l*, 2—*h*, 3—*a*, 4—*a*, 5—*k*, —*b*, 7—*e*, 8—*c*, 9—*g*, *10*—*d*, 11—*i*, 12—*f*.

Ans. to Q. 1.30. : 1—*j*, 2—*c*, 3—*g*, 4—*a*, 5—*d*, 6—*l*, 7—*i*, 8—*b*, 9—*k*, *10*—*e*, 11—*h*, 12—*f*.

Ans. to Q. 1.31. : 1—*d*, 2—*a*, 3—*h*, 4—*l*, 5—*g*, 6—*b*, 7—*c*, 8—*e*, 9—*j*, 10—*i*, 11—*f*, 12—*k*.

TYPICAL EXAMINATION QUESTIONS

1. What is actually understood by measurement ? What are the fundamental methods of measurements ? Discuss generally the phases of most measurement systems.
2. Explain the following terms in mechanical measurements :
   (*a*) Calibration (*b*) Sensitivity
   (*c*) Precision (*d*) Standard length
   (*e*) Accuracy (*f*) Uncertainty.
3. Discuss the role of workshop engineer as regards precision measurements and inspection. How attempts are being made to eliminate the operator's sense of touch and feel in the instruments ?
4. Explain the following terms : Repeatability, accuracy, precision. Also discuss the relationship of accuracy and cost.
5. What are the various possible sources of errors in measurements ? What do you understand by systematic errors and random errors ? How the random errors are analysed ?
6. What is the role of standardisation and standardising organisations in an industrial country ?
7. What do you understand by cosine errors ?
8. What is the effect of temperature variation on the measurement ? What is the standard temperature for measurement ?
9. What is the difference between gauging and measurement ?
10. What is the role of metrology in international trade ?
11. With globalisation of trade ; standardisation, quality and traceability of measurements have attained high significance. Why ?
12. Range of measurement and precision of measurement have inverse relationship. Why ?
13. The prescribed methods of precision measurements have to be strictly followed with all precautions and there cannot be any compromise for them. Why ?
14. How the advancements in precision of measurements and fine production techniques are taking place side by side ?
15. How digital electronics is changing the methods of measurements ?
16. Why it is essential to be able to determine the degree of uncertainty in precise measurements and how same is expressed ?
17. Discuss the importance of calibration system in metrology laboratory.
18. What do you understand by accreditation ?