Measurement of Out of Roundness

By

Syed Samsul Amin
Supervisor: Dr. Jay Raja
Summer 2004

Department of Mechanical Engineering and Engineering Science
The University of North Carolina at Charlotte
9201 University City Blvd.
Charlotte, NC 28223-0001 USA

Title: ***Measurement of Out of Roundness***

Contents:

1. Introduction

In common industrial usage, the term 'dimensional measurements' means the processes for determining the linear and angular magnitudes of components. In an extended usage, dimensional measurements also refer to the processes for assessing the geometric characteristics which can affect both the reliability of basic dimensional measurement and the functional adequacy of the part. The final goal is the economical production of parts in compliance with design specifications so as to ensure proper functioning of the manufactured product. For proper functioning of product the extent to which the part conforms to true geometric form is the most important criteria. Industry's need for higher accuracy has risen continuously and at a very rapid pace particularly in the last fifty years.

2. Definition

Roundness can in general is defined as 'trueness of form' of a circular part. In other words, a perfectly round part has all points of its perimeter equidistant from the axis. Roundness as defined by the standard - UBAB Y 14.5-1966 "Roundness is a condition of a surface of revolution, such as a cylinder, cone or sphere, where all points of the surface intersected by any plane, (1)perpendicular to a common axis (cylinder, cone), or (2) passing through a common center (sphere) are equidistant from the axis."

Tolerances of parts today are increasingly on the side of tenths of a micrometer. The necessity of understanding roundness was felt. However it must be realized that a perfectly round part cannot be produced by any known means of manufacturing. It is only a question of how close to a perfect round can one approach, expressed in practical terms to determine the characteristics and magnitude of departure in the actual geometric form of the object from ideal geometric form.

3. Nature of out of roundness

An ideal circle has all the points on its periphery equidistant from the centre. By defining roundness as stated above, it can be mentioned here that there is no ideal round part, but only how close to ideal roundness a part is. Before proceeding to know the source of out of roundness we would be better off knowing different forms of out of roundness. The point to be noted is that in practice the radius of a nominally round part tends to vary from point to point. Roundness is usually measured in individual cross sections of a part. This section is called the 'measured profile'. There are two cases; one case in which the part is truly round but not straight and another case where the part is straight but cross sections are not truly round. The first part though any particular cross section will be truly round, the centers of successive sections will not be in a straight line. This topic is a subject matter for separate study and will not be dealt in this material. This is stated here to bring out the differences in measured profile being round and cylindrical parts not true to its ideal geometric frame.

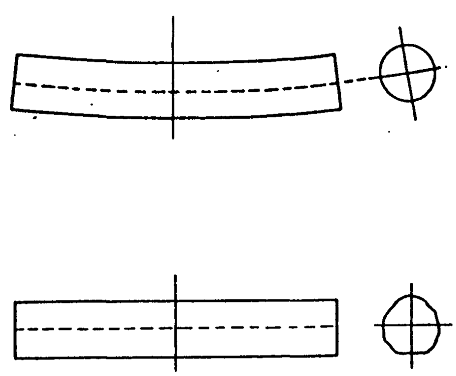

Figure 1 Three Dimensional Consideration of Circularity.

4. Sources of out of roundness

There are many causes for the radial variation of a nominally round part. The variations in shape shall greatly depend on the method of generation of the round part. Some of the common causes of out of roundness are: clamping distortion, rotational imperfections in the process of manufacture (spindle runout), vibration, heat, strain induced during machining, strain released after machining and residual surface texture left by the process. It should be understood that these variations in radius are not always detrimental to performance. In certain cases like the one with number of evenly placed lobes can behave almost as though the radius were constant.

5. Importance of roundness

The parts (of a machine) whose cross section is expected to be round, is normally defined by a single dimension, the diameter (maximum chord) and often with tight tolerance. This specification of a round part with diameter and tolerance is not meaningful, since the part can be out of shape but still conform to the specified tolerance. Therefore in addition to the tolerance limits, limits for form error will have to be specified to make the specifications more meaningful. A study of roundness and its measurement is essential in order to specify the required roundness. The roundness of parts like spindles, bearings etc., is very important since the proper functioning of these parts is crucial for generating a round part. A malformed spindle or a oval journal bearing will not only result in deforming the part that is being manufactured but also will result in the reduction of its life expectancy. Excessive heat generation, noise, vibration, variation in output torque etc., would be some of the effects of a non-round bearing or a non-round spindle that would lead to distortion of parts and consequent degradation of performance. Similarly critical parts whose function is to act as seals or effectively reduce leakage, in addition to its regular function, should be as true to its form as possible to be effective. Diesel injection plunger, hydraulic valve spool etc., fall in the above category. Hence, to be effective functionally it is essential that the parts should conform to their geometry, roundness in this case as close as possible.

6. Measuring Roundness

There are several methods measuring roundness all of which can be classified into two main categories. One is known as the intrinsic datum method. This is a conventional measurement where the deviations of a nominally round part, is measured with reference to a point or several points on the surface of the part being measured. Generally the object is supported on selected points of its surface and a sensitive probe signals the variations in the location of the momentarily contacted points, when the part is rotated either continuously or to specific positions by indexing. The magnitude of variations is an indication of the extent of form error. Diametrical measurement (two-point method), V-block method (three-point method), roundness measurement between centers are some of the methods of roundness measurement which are based on this principle. The other method, called the extrinsic datum method, of measuring roundness is by comparing with an external master profile, an ultra-precise spindle with almost perfectly run-out free rotation.

The difference between the above two systems of measurement is the datum surface with reference to which the deviation is stated. In the intrinsic datum method, the reference point is on the surface of the object itself while in the case of extrinsic datum method the reference is an external datum (master profile). Both systems have their own merits and demerits. Both of these systems are used widely. The choice of the system of measurement is dictated by the inspected parts' adequacy for its intended application. In other words the selected method of roundness measurement should give the required information with the least effort and cost.

The intrinsic datum method is widely used for roundness checking and is more adaptable for in-process measurements. It is relatively inexpensive and requires minimum fixturing. These equipments are rugged for use in adverse conditions. It is easy to operate and is quick. Unlike the other system, the object needs no centering or squaring adjustments. This method gives sufficient information for many applications, if the method is selected considering the dominant object conditions. However it must be pointed out that none of these methods will supply information in complete agreement with the standard specification of roundness since the basic principle differ from the concept of roundness measurement by comparing with an extraneous datum circle.

The extrinsic datum roundness measuring system supplies a true image of the geometric profile of the object by selective magnification to the extent required and suppression of inconsequential features. The evaluation and interpretation of the result can be done by different methods and an appropriate method can be applied based on the functional requirements of the product. The profile is measured continuously and not in discrete points as in the case of intrinsic datum methods. This continuous measurement of profile is recorded permanently on a chart or stored as data in a computer which can later on be referred for thorough analysis.

a) Intrinsic datum methods

As mentioned earlier, there are various circumstances where intrinsic datum methods will be adequate or may even be preferable to inspection by extrinsic datum methods. Each of these methods is discussed briefly in subsequent sections.

i. Diametrical measurement

The simplest of methods is to find the diameter using a micrometer or a dial gauge. This type of measurement will give the absolute measurements of diameter (or only variations in diameter with respect to a preset dimension). In cases such as shown in Figure 2(Left) below, constancy of diameter will be maintained without the part being truly round (see Appendix 1). From the figures it is clear this method of roundness assessment will fail if the parts are symmetrically lobed. However if the departure from roundness is non-symmetrically distributed (i.e. lack of constant diameter) then it can be easily identified. Hence this method will be suitable where the primary requirement is that of constant diameter rather than perfectly round part.

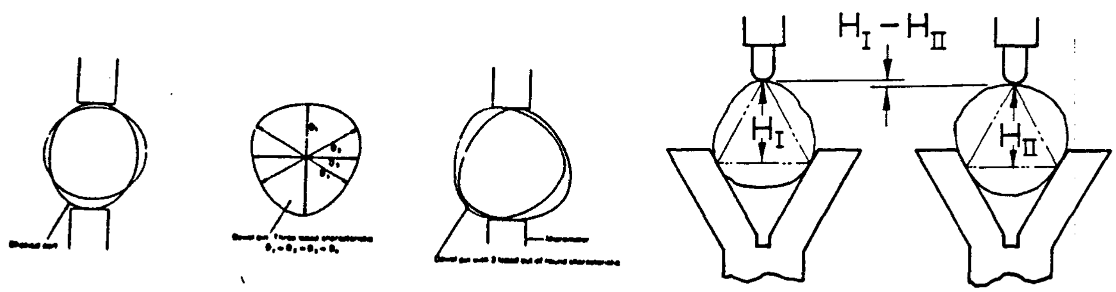

Figure 2 (left) Diametrical Method; (right) Schematic illustration of the form conditions measured when supporting an imperfectly round part in an appropriate V-block.

ii. V—Block method

The part is supported on a V-block (Figure 2). The walls of the V-block being symmetrical ensure that the contact points of the part are kept at a constant level in relation to the reference position of the gage point. The instrument probe tip is made to contact a third point symmetrical to the points in contact with the flanks of the V-block. These three points form an imaginary isosceles triangle. The departure from roundness is calculated from the variations in the lengths of the chords joining the two support points and the indicator.

V-block offers a convenient way of holding a round object by gravity, also assisted by the gaging pressure of the indicator acting in the direction of gravitational pull. By this method non-symmetrical out of roundness can be detected easily (see Appendix 2). It is simple and convenient and hence widely used. The roundness inspection using V-block is a comparative kind of measurement since the reference dimension is one of the multiple readings taken for a measured profile (generally the first reading is taken as the reference dimension). However the variations measured are not radial variations. The variations are proportional to the radial variations only when the undulations are of uniform height and spacing and the V-block used for support has the appropriate angle. The sensitivity is highest when the crests engage the V-block and the gage tip at the same time (in phase). The sensitivity is least when the gage tip engages the trough and the V-block engages the crest (out of phase).

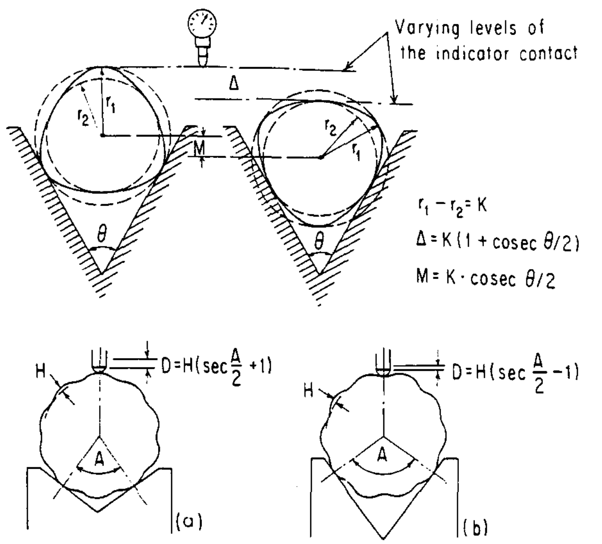

Figure 3 The geometric analysis of V-block supported roundness inspection. (Upper) Interrelation of the lobe spacing and of the V-block angle. (Lower) Effect of V-block's included angle (180º-A) on the indicator readings in relation to the radial range(H) of the circumferential undulations. The examples are based on equally spaced undulations and show the applicable formulas for : (a) The most sensitive V-block angle, (b) The least sensitive V-block angle.

Geometric analysis:

The variations as measured by the gage are the combined value of two distinct components. The first one is that radius of the part which coincides with the bisector plane of the V-block. The second one is the radius pertaining to the contact points of the part with the V-block, reflected in the gage reading as the change in the level of the axis of the round part. This is indicated in the Figure 3. The two different radii are indicated as two concentric circles, the circumscribing (r_1) and the inscribing (r_2) circles. The Figure 3 shows two different orientations of the object in the V-block and the resulting variations in the level of the surface element contacted by the indicator, as well as of the axis, are pointed out.

Equation for displacement of gage tip

Displacement of gage tip, D = Change in the level of the axis of the round part + difference in radius of the part which coincides with the bisector plane of the V-block.

$$D = (r_1-r_2) + m = k + (k / \cos(a/2)) = k\,(1+k \sec(a/2))$$

The above equation represents the displacement of the gage tip for in-phase condition. In case of out of phase the equation will be,

$$D = k(\sec(a/2) - 1)$$

The equations show that for the same object, the displacement of the gage tip can be a maximum for a certain V-block (included) angle. Hence the appropriate V—block is chosen in such a way as to maximize the displacement of the gage tip for a given part. For a theoretical part having undulations which are uniformly spaced and have uniform amplitude, the appropriate angle of the V-block is,

$$\theta = 180 - (360/n)$$

where, ‘n’ is the number of uniformly spaced undulations.

A V-block of appropriate angle will exaggerate the extent of out of roundness, when the crest to valley difference is taken as the characteristic value of out of roundness. The following Table 1 will show for a few typical numbers of undulations, the appropriate V-block angles, as well as the factors by which the indications on a part of theoretically regular form are increased over the actual out of roundness value.

Table 1 Conversion Factors for Roundness Measurement using V-Blocks.

Number of uniformly spaced undulations on the object surface	The "appropriate" included angle of the V-block	Factor by which the indicator readings are increased over the actual radial out-of-roundness
3	60°	3.00
5	108°	2.24
7	128° 34'	2.11
9	140°	2.06

The V-block method can be used effectively to detect presence of out of roundness due to odd number of lobes. However the value of out of roundness calculated by this method should be treated with circumspection. This method is sensitive to the included angle of V-block. Best results can be achieved only when the V-block with appropriate angle is used. Moreover there is a tendency in this method to indicate a cumulative value of errors arising from contour characteristics at both the gaging and the supporting points. Generally this tends to indicate a higher value of out of roundness. Also we know that the figures obtained for out of roundness are exaggerated. The figures indicated in the Table 1 above are calculated for a theoretical model and are not exactly applicable for actual parts. Moreover in the case of even number of lobes, V-block frequently can be concluded that V-block method is simple and effective when the primary objective is to detect the presence of out of roundness due to odd numbered lobing and the values obtained by this method are a good approximation rather than exact.

iii. Bench Center Measurement

The bench center method is only suitable for parts that are manufactured with machine centers. In this method, parts to be measured are mounted between the centers of a bench center and than rotated while a test indicator (mechanical or electronic) is in contact with the surface (Figure 4).

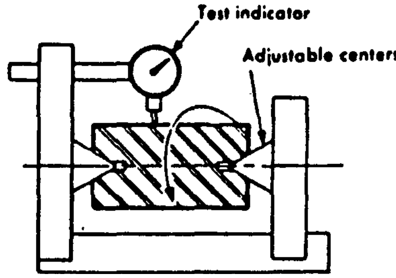

Figure 4 Measurement of out of roundness using the bench center method.

Reliability is dependent on many factors such as the angles, alignment, roundness and surface and surface condition of the centers and center holes. Any or all of these factors may combine in a given inspection, creating a high degree of uncertainty as to the exact nature of the error. With the bench center measurement method, parts that are within the tolerance specification are acceptable. However, parts that are not within the tolerance specifications are may also be acceptable because of errors inherent in this method. Out-of-roundness error can be caused by an improper alignment of the bench centers and/or center holes. The angles of the centers may also be different than the center holes. Other sources of error include out-of-roundness center holes and centers, inadequate surface condition of centers and center holes, and bowed parts.

b) Extrinsic Datum Method

In the extrinsic datum method, precision instruments are used to measure part circularity. The part is mounted on either a stationary or rotating table, depending on the instrument design, with an electronic probe (stylus) contacting the surface of the part. When the part or spindle is rotated, the instrument prints an enlarged scale representation of the surface configuration on a polar chart graph. In addition to printing the surface configuration, most precision spindle instruments also print a reference circle for verification.

Measuring circularity with precision spindle instruments supplies, a true image of the geometric condition of the part by selective magnification. Magnification rates and suppression of inconsequential features can be varied to enhance the most meaningful aspects of circularity condition. The image of the part can also be evaluated by different methods of interpretation; the method selected is based on the functional requirements of the part. Continuous tracing around the entire surface in the selected plane minimizes the possibility of disregarding errors that can be missed by point-to-point measurements. In addition, the graphical representation of the circularity conditions is valuable for a thorough analysis and serves as a permanent record.

A. Polar graph interpretation

The trace produced by the polar graphing instrument is simply a graphical record, suitably magnified, of the displacement of the stylus of the measuring instrument. The out-of-roundness value can be assessed by the differences between the maximum and minimum radial ordinates of the profile measured from a specific center. The four methods by which this center can be located are:

1. *Minimum radial separation (MRS)*
2. *Least Square circle (LSC)*
3. *Maximum inscribed circle (MIC)*
4. *Minimum circumscribed circle (MCC)*

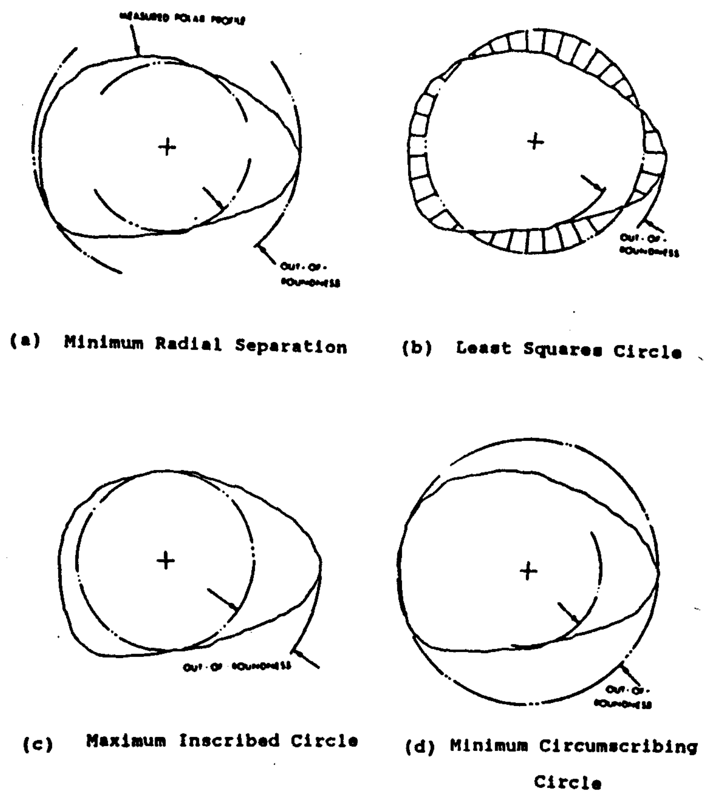

Figure 5 Reference Figures.

1. Minimum radial separation

In the minimum separation or minimum zone circles method, two concentric circles ar, chosen so as to have the least radial separation and yet contain between them, all the polar traces (Figure 5a). The radial separation is the measure of the out-of-roundness value. The proper location and size of the inscribed and circumscribed circles are most conveniently determined with engraved or printed circles on transparent templates. The radial separation can be noted from the engraved circles directly or measured from auxiliary concentric circles that can be drawn from the center Located by the engraved circles. This method requires at least two outer contact points and two inner contacts points must occur alternately, but not necessarily consecutively, for one complete profile traverse.

2. Least Square circle

In the least square circle method, a theoretical circle is located within the polar profile such that the sum of the squares of the radial ordinates between the circle and the profile is minimum. The center of the circle is than used to draw a circumscribed and inscribed circle, on the profile graph (Figure 5b).The out-of-roundness value is than the radial separation of these two circles. The least squares circle (LSC) and its center is unique because there is only one that meets the definition. The accuracy of the center and radial zone width depends on the number of ordinates taken. Manual graphical assessment can be tedious and time-consuming, but digital instruments and/or computers can reduce the time and efforts required for LSC evaluation.

3. Maximum inscribed circle

In the maximum inscribed circle method, the profile center is determined by the largest circle that can be fitted inside the profile (Figure 5c). The center can be determined by trial-and-error with a bow compass or with engraved circles on the transparent template. The out-of-roundness of the part is the maximum outward departure from the inscribed circle.

4. *Minimum circumscribed circle*

In the minimum circumscribed circle method, the profile center is determined by the smallest circle that contains the measured profile (Figure 5d). From this center point, an inscribed circle fitted inside the profile is drawn. The out-of-roundness is the maximum inward departure from the inscribed circle.

B. Operating Parameters

In addition to graph interpretation, the out-of-roundness value is influenced by the instrument response, stylus size and geometry, and stylus force. Circularity measurement using precision instrument is based on the coincidence of the master axis with the part axis. The master axis is represented by the axis of rotation of the instruments the part axis is represented by en imaginary straight line at an equal distance from the surface of a basically round part or feature. Before the part surface can be traced with the stylus, the center of the part and the center of the rotational movement producing the reference circle must be coincidental, which includes correcting any angular misalignment between the part axis and the master axis.

1. *Instrument response*

The instrument response referred to as the cycles per revolution (CPR) response, is the sensitivity of the instrument to surface irregularities. The value of the CPR response should be selected based on the number of radial deviations required to be represented on the polar graph. If all the deviations were represented on the graph, the high frequency surface irregularities could mask the lobing condition or form the profile.

2. *Stylus size and geometry*

The stylus is in direct contact with the part surface and transmits any surface profile variations to the pickup. For most applications, the tip of the stylus is ball shaped and 1/16″ to 1/8″ (1.6 to 3.2 mm) in diameter. When fine details of the profile are required the smallest size tip radius should be used.

3. *Stylus contact force*

The appropriate stylus force to maintain adequate contact with the part surface depends on the hardness, flexibility and maximum compressive strength of the part material; the rotational speed and mass of the stylus radius. To minimize surface damage from high compressive stresses, yet maintain a high contact pressure for consistent measured profiles, the maximum stylus force for each nominal stylus radius should be selected.

C. Polar graph magnification

When a single measured polar profile is to be measured for out-of-roundness, the polar graph magnification should be either the largest value available so the profile is completely contained within the chart boundaries or the lowest value commensurate with the best assessment of the part features or tolerance. At the lowest magnification condition, the distortion arising from various systematic causes will be minimized. When a series of measured profiles is needed, such a. concentricity, taper, or other interrelated measurements, the polar graph magnification should have limit to the lowest value available within the series that will accomplish the measurement objectives. By doing so, profile comparisons are facilitated. Increasing the magnification often requires recentering of the part to reduce the profile miscentering distortion.

D. Equipment

In addition to micrometers, V-blocks, and indicators, precision spindle instruments are commonly used to measure circularity. The two types of instruments are: (1) those in which the part rotates while the stylus and pickup remain stationery and (2) those in which the stylus and pickup rotate while the part remains stationary (Figure 6). Each type has its advantage and more suitable for certain type of measurement; the choice depends on the measurements to be made and size and shape of the parts being measured.

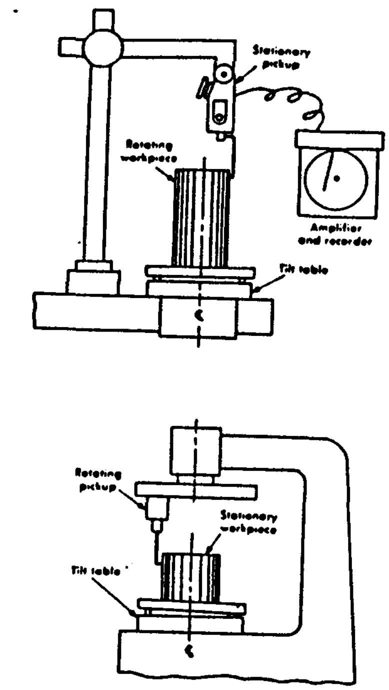

Figure 6 (Upper) Rotating workpiece and (Lower) rotating pickup types of precision spindle instruments for roundness measurements.

E. Operation

In operation, the stylus of the pickup is brought into contact with a point along the selected surface element of the part and adjusted to the position of zero indication. The rotary displacement movement of the machine is started while the stylus remains in contact with the part surface. Pin uninterrupted succession of an infinite number of contact points is thus created, describing the complete circle around the surface of the part.

Variation in the distance between the axis of rotation and contacted points along the surface element cause the stylus to deflect. These deflections produce electrical signals in the pickup that are electronically amplified at a preset rate and than displayed on a meter or by a recorder. The recorder reproduces the deflection on a polar or linear graph. The distance between the axis of rotation and any contact point on the part surface is considered to represent the radius of the momentarily contacted surface point. The variations of the consecutive radii are the measure of departure from perfect circularity as presented by the displacement path of the stylus.

There is one fundamental important limitation of such instruments. It is normal to measure only the radial variation between the surface of the workpiece and a nominal circle (represented by a known point in the transducer) having a radius equal to that of the workpiece. For display purpose the variation is magnified and superimposed onto a convenient arbitrary radius for plotting as a polar graph of the errors. The result is as though the part is first scaled up, and every point on the resulting graph is moved back towards the center through a constant distance. For example in Figure 7 (a) represent the part, (b) the part scaled up and (c) the result of moving all the point towards the center by an amount ‘X’. A cylindrical specimen slightly flatted at intervals, as shown in Figure 8 plots as a figure having convex sides at a low magnification but appears to have flat aides or even star-shaped, if the magnification is progressively increased.

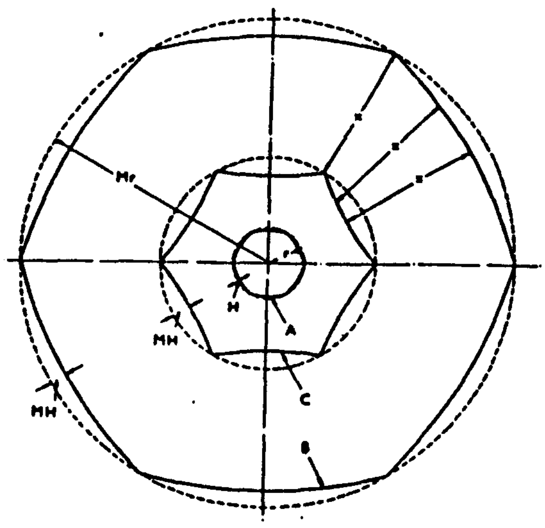

Figure 7 Graphical Representation

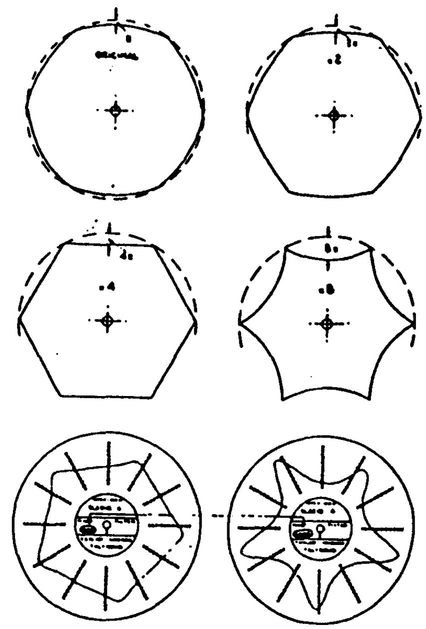

Figure 8 Effect of Magnification.

F. Numerical Measurement

The out-of-roundness value (oorv) is numerically assessed as the difference between the maximum and minimum radial ordinates of the profile measured from a specific center. There are four ways in which the center may be located:

1. Minimum radial separation.
2. Least square circle
3. Maximum inscribed circle
4. Minimum circumscribed circle

7. Reference Criteria for Roundness Measurement:

Most measurements of nearly circular parts use a precision spindle to create a relative rotational motion between part and a displacement transducer mounted radially with respect to the axis of rotation. The signal from this represents a combination of out-of-roundness of the part and the variation of radial distance of the surface from the axis caused by relative eccentricity between them (21. Traditionally these variation, are magnified and superposed on a convenient nominal radius which is totally unrelated to the actual dimensions of the component. The Output of the instrument in this form ia referred to as the polar chart. Thus virtually all practical roundness measurement involves the self evidently named concept of radius suppression. This radius suppression is illustrated in Figure 9(a).

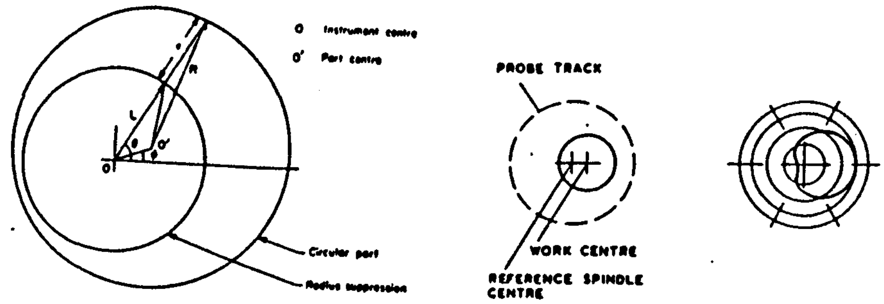

Figure 9(a) Radius Suppression (left); (b) Distortion of charted profile due to eccentric staging of workpiece (right).

Any eccentricity between the center of the part and the rotational axis of the measuring instrument causes a distorted representation of the profile. The profile distortion of a miscentered but nominally round part is shown in Figure 9(b).

The Measurement System:

It is convenient to describe the measurement process in terms of three frames of references. Initially there are hypothetical component co-ordinates in which the points of the surface have a fixed relationship to each other independently of its orientation in space. Then to measure the surface it is expressed relative to instrument co-ordinates which locate it in the space and as it is not possible to position a component perfectly relative to an external frame of reference, an error due to misalignment is included i.e. presence of eccentricity. Thus eccentricity is clearly identified as being a property of the transformation from component to instrument coordinates. The normal instrument operates by first radius-suppressing and then magnifying the profile, so that its output represents a transformation of the instrument coordinate frame into a chart coordinate frame. Therefore roundness profile analysis involves the interpretation of data back through these coordinate transformations. i.e. the interpretation of chart data in terms of instrument and component frames of reference (appendix-3).

8. Conclusion

The condition of circularity, external or internal, demands the most attention of any form or shape measurement because this type of geometry comprises the great majority of mechanical form conditions in manufacturing operation. Different measurement systems of out of roundness are explained briefly in this article. As far as precision engineering concern, it needs a more detailed study to understand all the aspects of out of roundness.

Appendix-1

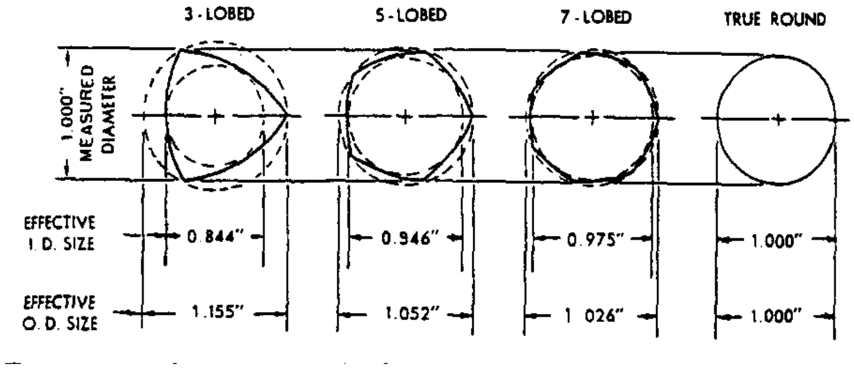

Figure Conventional although exaggerated representation of iso-diametrical out of roundness and its effect on the diameter measured between two parallel planes in contact with the part surface. Note: the drawing shows conditions which are accentuated by assuming equal spacing of the lobes and regular circular arc form of the connecting perimeter section.

Appendix-2

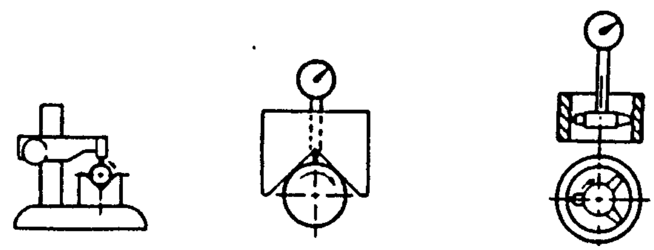

Figure V-Block methods

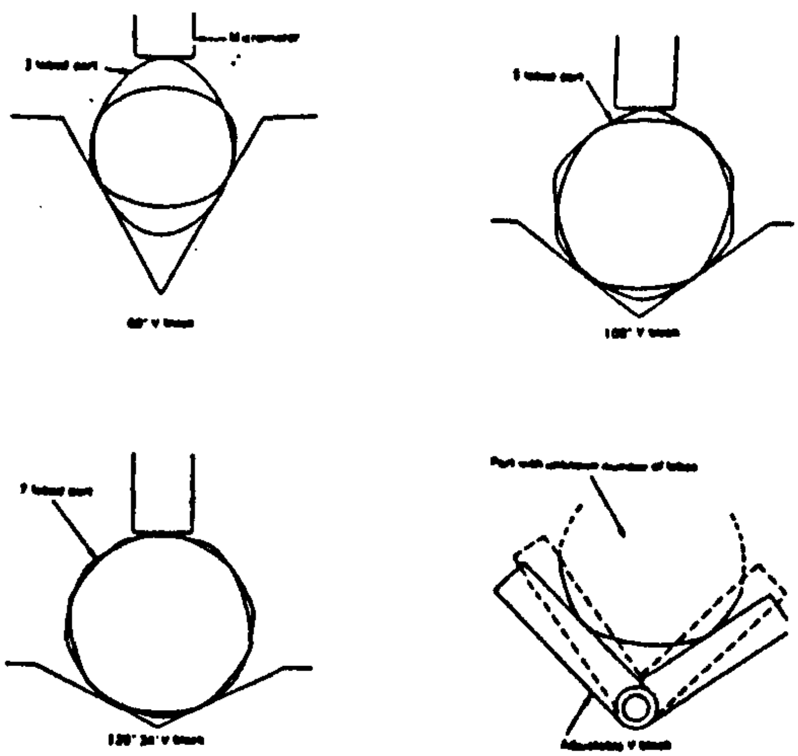

Figure Fixed and Adjustable V-blocks.

Appendix -3

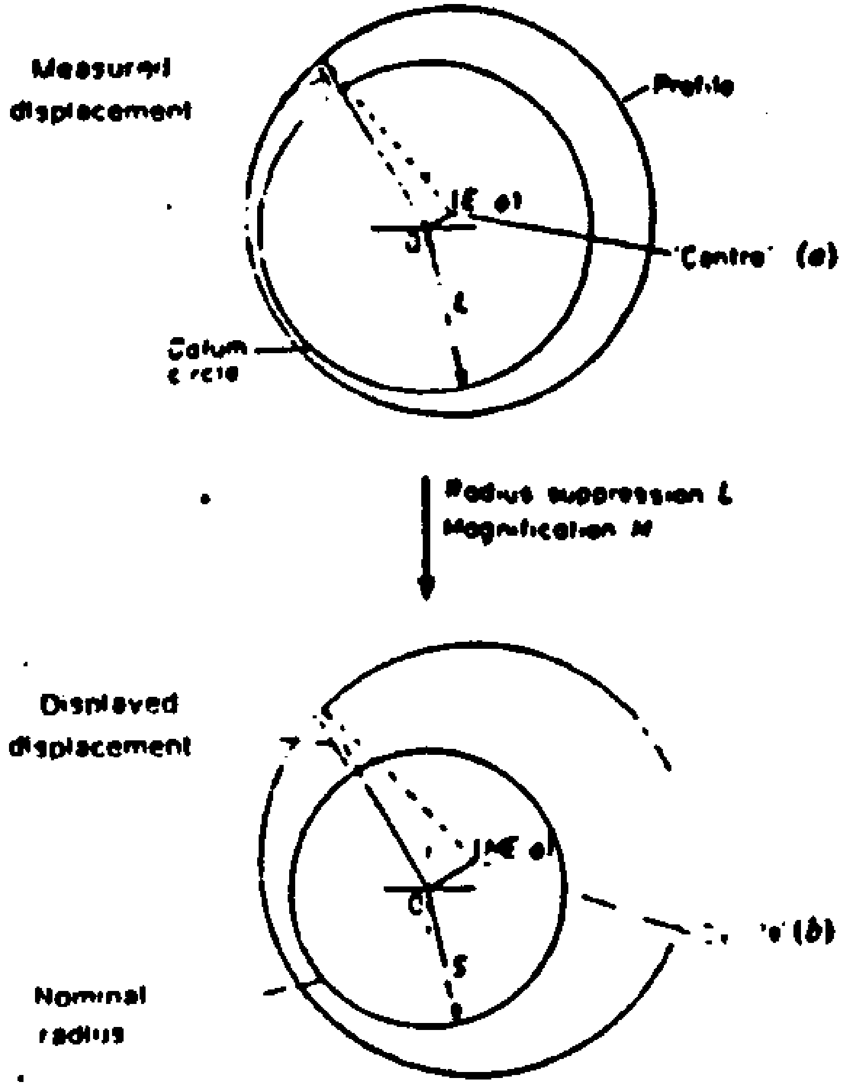

Figure Principles of roundness measurement using radius suppression (a) Instrument coordinates, (b) chart coordinates