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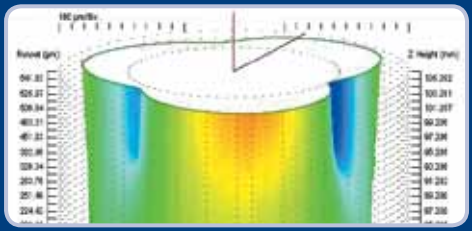
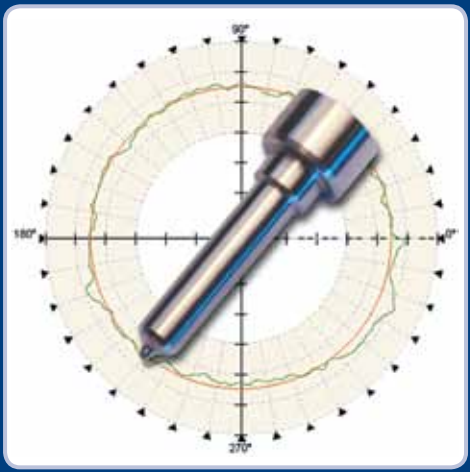
Exploring Roundness





A fundamental guide to the measurement of cylindrical form

3rd Edition

Exploring Roundness

A fundamental guide to the measurement of cylindrical form

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Preface

This book is intended to give the reader an introduction to the basics of roundness and cylindricity together with their measurement. Other types of form are also included (e.g. flatness, straightness & parallelism) which are often associated with components having a cylindrical form. It makes no pretense at being either a detailed study of the subject, nor a comprehensive reference source. However, for those seeking an overview of the subject it is an ideal introduction. The emphasis is on the metrology of rotationally symmetric parts, rather than their manufacture or use.

The reader is assumed to have a general engineering background but no prior knowledge of roundness metrology is required.

Metric units are used throughout. For those more used to English units, approximate equivalents are:

1 mm	(millimetre)	= 0.040 in	= 40 thousandths
1 µm	(micron)	= 0.000040 in	= 40 millionths
1 nm	(nanometre)	= 0.0000004 in	= 0.04 micro inch

1 mil (thousandth of an inch)	= 25 µm
1 micro inch (millionth of an inch)	= 25 nm

Chapter 1 - Introduction

"There shall be standard measures of wine, ale and corn (the London quarter), throughout the kingdom. There shall also be a standard width of dyed cloth, russett and haberject, namely two ells within the selvedges. Weights are to be standardised similarly."

(Magna Carta, clause 35, AD 1215)

"When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

Lord Kelvin (1824-1907)

It has been said that the greatest benefits to mankind have derived firstly from the invention of the alphabet and secondly from the invention of the wheel. Certainly without the latter there would be no technology - no civilization as we know it today.

Look around and consider how much your life depends on machines with rotating parts. Not only the motorcar and the tools you use, but the smallest watch and the largest power station. In any engineering facility it will be seen that many machines are making round or cylindrical components - shafts, bearings, gears, bushes, ball bearings, wheels. All have one thing in common: they are ROUND. But how round?

As the drive for ever-increasing performance and energy efficiency continues, tolerances and clearances are decreasing. It is no longer sufficient to simply assemble parts to determine if they are "good or bad" or "pass or fail". Measurement must take place throughout the entire manufacturing process (**see Figure 1**). The results of such measurements should be integral to the development of a capable manufacturing process that delivers parts that are capable of the required performance criteria at a cost effective price. Only with suitable instrumentation and good metrology practice can we avoid Lord Kelvin's "...knowledge of a meagre and unsatisfactory kind". This book starts you on the road to understanding and solving those issues.

Performance control

Consumers' expectations of quality, reliability and endurance have increased greatly over recent years. Without suitable research into determining the ideal "functional parameters" of a workpiece and without quality control ensuring it is maintained, consumers and manufacturers are likely to experience excessively high warranty claims and poor consumer satisfaction levels.

The use of the basic parameters such as roundness, squareness, parallelism and size often ensure that a component will "fit", however use of more advanced parameters may help ensure that the performance is acceptable in terms of such factors as:

(i) mean time between failure (MTBF)
(ii) vibration/noise
(iii) heat generation
(iv) cosmetic appearance

Manufacturing process control

Modern manufacturing is a highly competitive environment. Efficiencies and yield rates must be maximized. An effective measurement process is essential in ensuring that a process is kept under control and that "capable" machines are identified and used. A "capable" machine is able to make parts to the required tolerance (and therefore not produce scrap) without being over specified (and therefore unnecessarily expensive).

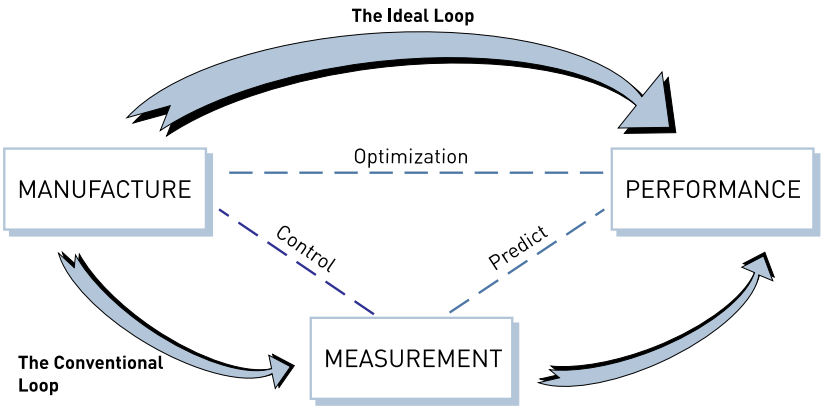


Figure 1: Stages in the life of a manufactured component

Instruments have been developed for measuring roundness and associated parameters and these are now in common use. It is important for anyone connected with engineering - either as a designer, machine tool operator or inspector - to have a basic understanding of the principle of these instruments, their capabilities and limitations and how to interpret the results which they provide. Not only can these results be used to accept or reject components for roundness, but they can also be used to monitor the manufacturing process, as shown in **Figure 1**.

Using a suitable inspection policy, appropriate equipment and the right choice of parameters it is possible to characterize such process factors as:

(i) **Machine tool performance** Determine if the machine consistently and repeatably produces the same parts within the correct tolerance bands.

(ii) **Tool wear** Excessive wear indicates a poor choice of cutting parameters or lubricants.

(iii) **Fit** Often a part is not assembled until much later than the time it is first produced. If the part is to size but will not fit due to form errors then a disproportionate cost can be incurred in rework.

(iv) **Process stability** While a single machine may be capable of producing quality parts it is not uncommon for the same parts to be made on different machines (possibly not even in the same manufacturing site or country). It is therefore important that the total process be controlled.

The scale of the problem

As with all engineering subjects, the solution is dependent on the scale of the problem.

While marine drive shafts and power station turbines may have bearings of 1 meter or more in diameter, the vast majority of applications are in the 5 to 200mm range.
At the small extreme, some of the smallest ball bearings have rolling elements under 0.5mm in diameter.

The typical out-of-roundness on an automotive bearing journal is around 5μm and represents the less accurate end of roundness being considered in this book. In the mid range are items such as fuel injectors and general-purpose bearings where tolerances around 0.25 to 0.5μm are typical. At the ultra precision end of the scale, NASA's Gravity Probe B has mechanical gyroscopes with spheres claimed to be the most "perfectly spherical" ever made. They are about 100mm in diameter and the maximum deviation from "perfect" is 7nm.

Structure of this book

In the next chapter we look at what constitutes roundness: surprising as it may be, roundness is a more complex parameter than it first seems.

Chapter 3 moves on to principles of measurement: although a certain overlap with **Chapter 7** (Instruments) is inevitable it attempts to look at the principles of measurement rather than the mechanics of how it is achieved.

Chapter 4 (Putting a number to it) introduces the parameters that are used to quantify roundness. As the writers of Magna Carta realized nearly 1,000 years ago, without standard definitions of parameters there can be no trade. Today the standards are provided by national standards bodies and, increasingly, the International Standards Organization (ISO). In this book we refer to ISO standards and note national deviations where appropriate.

Chapters 5 & 6 then go on to look at more advanced features such as cylindricity, parallelism, coaxiality and flatness.

Chapter 7 (Instruments) looks at the hardware and software for measuring roundness and cylindrical form. Subsequent chapters raise some issues about how to get the best out of your hardware and solve particular process control problems.

The book is rounded off with some useful references and definitions.

Chapter 2 - What is roundness

Many manufactured components contain elements that are "round" in cross section, the simplest being a shaft and a hole. Such simple geometries are widely used: **Figure 2** shows a typical application of a rotating shaft in a bearing housing (the hole).

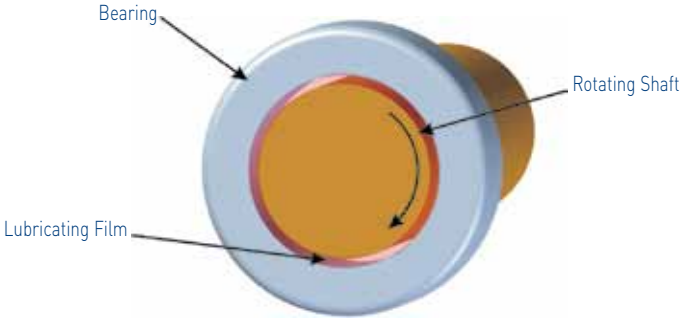


Figure 2: Typical application of a bore & shaft arrangement

Providing that both are "round" and the fit is not too tight or too loose, the shaft will run smoothly enough - better still if lubricated. But is this sufficient? Will the combination of shaft and bearing continue to give satisfactory performance when heavily loaded and after many years of use? Also, does the lubricant have the best chance to do its work effectively?

Figure 3: Magnified view of outer diameter of shaft

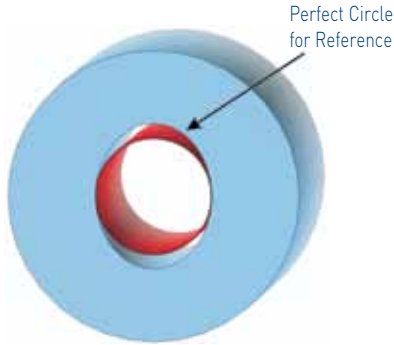


Figure 4: Bore shows ovality

The answers to these questions depend on what we mean by round. The bearing or shaft may appear to be round to the eye - it may even have a constant diameter when measured with a micrometer, but when we examine the shape on a greatly enlarged scale it could be as shown in **Figure 3**. It is clear that the lobes or peaks at (p) will carry most of the load of the shaft when it runs in a plain bearing. The thickness of the lubricating film must be kept within limits if it is to act as intended, but in **Figure 3** the thickness of oil film in the valleys (v) will be considerably greater than at (p). Similarly the bearing could have a bore

that is not truly circular: it might be slightly oval as shown (exaggerated) in **Figure 4**, with the same results. In either case the shaft/bearing combination will act less efficiently than the designer intended.

Diameter

Many people wrongly believe that it is sufficient to measure the diameter of a workpiece in several places – the difference in readings equating to the out-of-roundness. Perhaps the easiest way to dispel ideas that such a methodology is valid is the example of measuring a British 50 pence coin. In **Figure 5** it can be seen that the caliper reading when measuring the coin is identical irrespective of the coin's orientation, and yet it can be seen to be "out-of-round".

Figure 5: Although the radius varies, diameter of a British 50 pence coin remains constant

The difference between measured size and effective size

As demonstrated above, the measurement of diameter cannot be relied upon to measure out-of-roundness.

An important consequence of the out-of-roundness is that it will affect the fit between components.

As an example, consider the three-lobed workpiece shown in **Figure 6**. This has a measured diameter of exactly 25mm, so one would expect it to fit into a 25mm diameter hole. In fact it will not fit because of the out-of-roundness. In this particular example the smallest round hole that this figure will fit into has a diameter of 28.9mm (**Figure 7**).

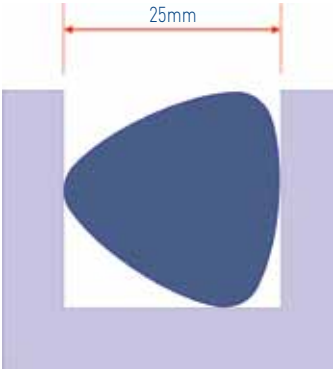


Figure 6

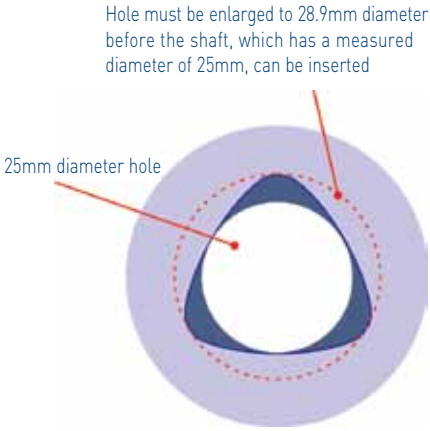


Figure 7

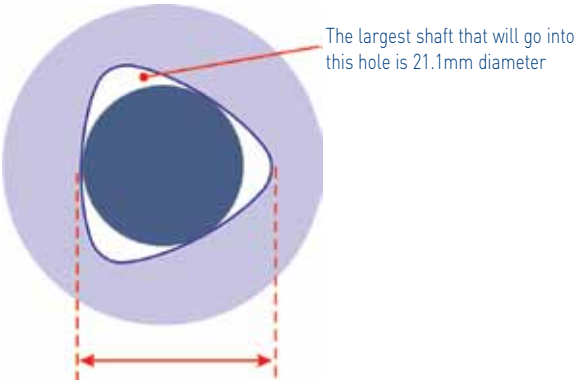
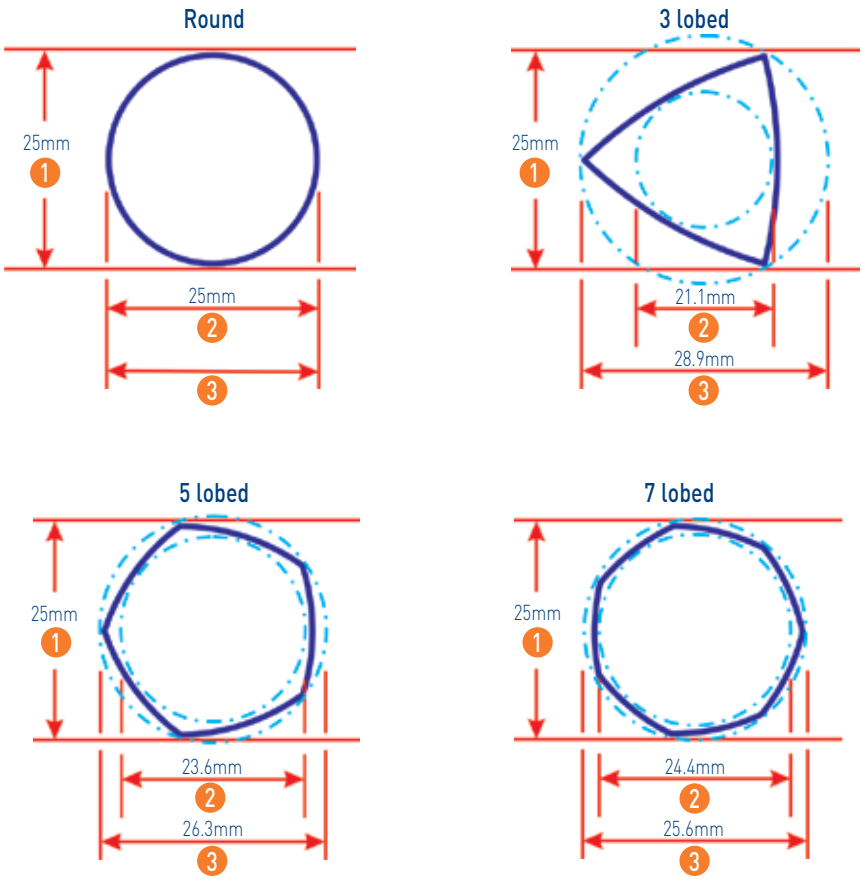


Figure 8

Similarly, a three-lobed hole (**Figure 8**) having a measured diameter of 25mm, will not take a truly round 25mm diameter shaft: in fact the largest shaft that will go into the hole has a diameter of 21.1mm Thus the effective size of these two pieces is 28.9mm for the shaft and 21.1mm for the hole, although both have a measured size of 25mm diameter. Similar differences between measured size and effective size are exhibited by parts having any odd number of lobes (**Figure 9**), so the shape (i.e. roundness) of a workpiece can affect its size as measured in the conventional way.



1 Measured dimension
2 Effective internal size
3 Effective external size

Figure 9: Effect of lobing on measured and effective diameters

Chapter 3 - How do we measure out-of-roundness

Vee-block method

As we have seen in the previous chapter, use of diameter has significant drawbacks in the measurement of out-of-roundness which is always assessed independent of size. Therefore we must adopt some other method.

The simplest method is to place the part in a vee-block and rotate it in contact with a dial gauge or similar indicator (**Figure 10**). Rotate the part slowly and carefully by hand, taking care not to disturb the vee-block or gauge stand and making sure that the part rests on the two arms of the vee all the time. If the part is truly round, with negligible irregularity, the pointer of the gauge will not move. If, however, the part is out-of-round the irregularities will cause the part to move up and down (**Figure 10**) as they contact the sides of the vee. In addition the irregularities themselves will displace the plunger of the gauge as they pass under it.

The pointer movement will be greatest when either peaks or valleys contact the plunger and arms of the vee simultaneously (**Figure 10a**) and the movement will be least when a valley is under the plunger and peaks are contacting the vee-block (**Figure 10b**), and vice versa. The amount by which the gauge pointer is displaced will depend not only on the height of the irregularities ("peaks" and "valleys") but also on their angular spacing and the angle of the vee-block (**Figure 11**).

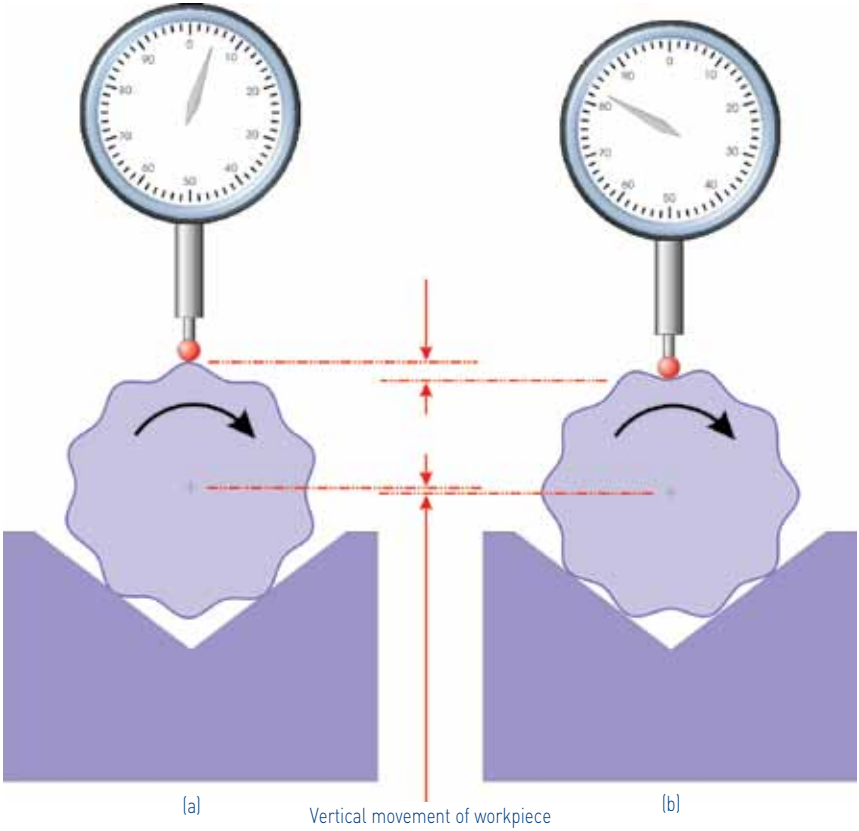
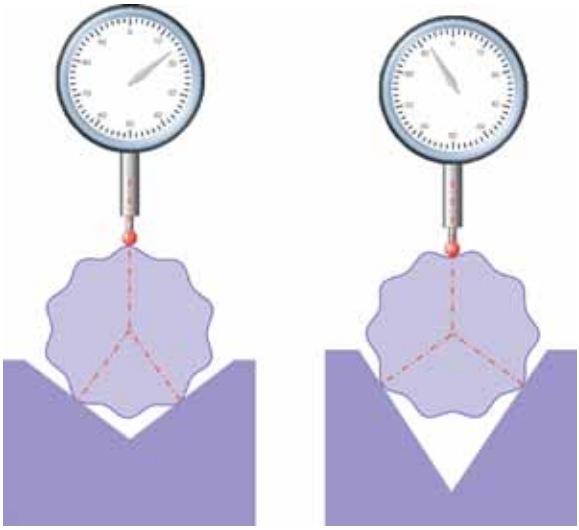


Figure 10: Measured height difference at different rotational positions of the workpiece

This vee-block measurement of roundness is essentially a three-point method and there are several variations in the way it can be applied. For large parts an inverted arrangement is sometimes used (**Figure 12**), the indicator and the feet, representing the arms of the vee, being mounted in a frame which can be moved around the part. A similar frame can be used to check the roundness of large bores (**Figure 13**). Long shafts may have to be supported on two similar vee-blocks with the dial gauge positioned between them (**Figure 14**), but the readings obtained will be further influenced by sag and lack of straightness of the shaft.

However the three-point method is applied, it will always suffer from the limitation that the results may vary according to the vee angle and the spacing of the irregularities. It also gives a false impression when the undulations are regularly spaced, as each one influences the dial gauge three times as the part rotates; once when an undulation passes under the plunger and once when it contacts each arm of the vee.



(a) (b)

Figure 11: Angular spacing and the angle of the vee affect the measurement

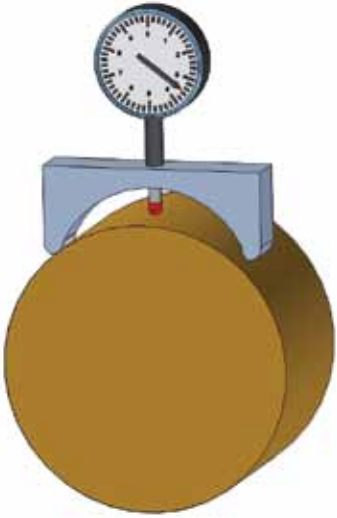


Figure 12: Measuring large shafts

Figure 13: Measuring large bores

Nevertheless, the three-point method is simple to apply and workshop inspection is often based on the use of one or two vee-blocks of defined angle. The indicator readings, although not fully informative, are by agreement accepted as a sufficient assurance that a part is round enough for its intended purpose, provided that the roundness is not too critical.

A different, and more accurate method, is to rotate the part between centers (**Figure 15**), but this is really only applicable to parts which have been machined on centers or provided with sufficiently accurate center locations. If the dial gauge is positioned as shown, the readings will not only represent the out-of-roundness but will also include variations due to sag and curvature of the part and imperfect centering. Positioning the gauge near to one end of the part will eliminate errors due to sag and curvature, but the out-of-roundness at this position may not be typical.

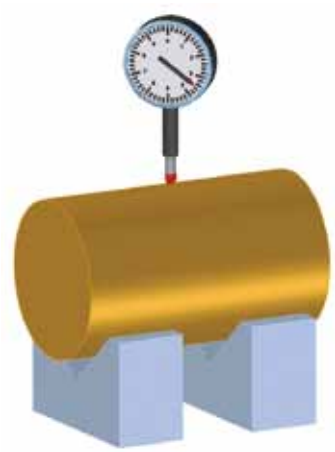


Figure 14: Measuring with vee blocks

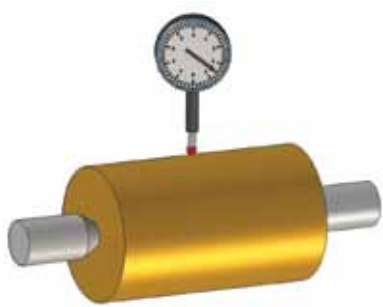


Figure 15: Measuring using centers

The mechanical dial indicator can, of course, be replaced by an electronic gauge but the whole arrangement is subject to the limitations of mechanical accuracy mentioned previously.

Coordinate measuring machine

Another method often considered acceptable is the use of a coordinate measuring machine (CMM). A standard CMM has three accurate, orthogonal axes and is equipped with a touch-trigger probe. The probe is brought into contact with the component being measured and its position is recorded. Such measuring systems are very versatile and are often used to measure and analyze multiple dimensional and geometric inter-relationships on a workpiece. Although such devices work well for basic geometric characterizations of a workpiece their limitations on measuring features such as roundness and cylindricity are often ignored.

Figure 16 demonstrates the limitations of CCM assessment of out-of-roundness (exaggerated to make the errors visible). In this example 4 probing points are used to assess roundness geometry using a CMM. As can be seen the result indicates that the bores are perfectly

round and have the same size but different centers. Most CMM manufacturers recommend taking a minimum of 7 data points to assess roundness. This would help ensure that the calculated center was much more accurate than that shown in **Figure 16**, but it would only marginally improve the accuracy of the roundness assessment.

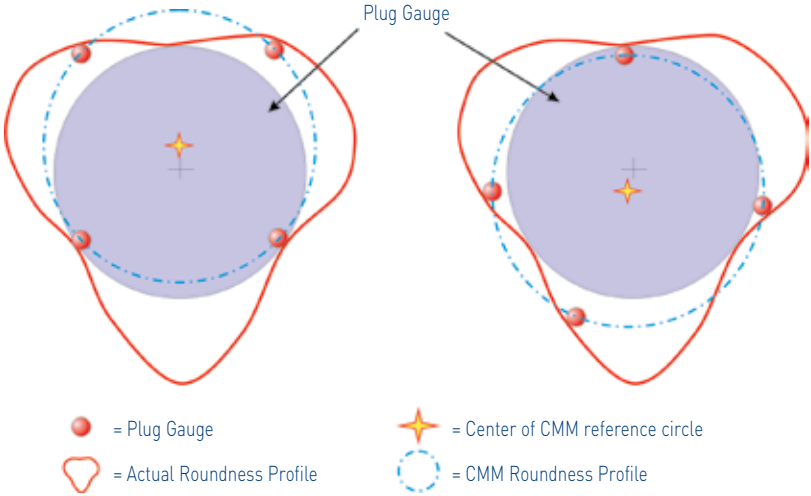


Figure 16: CMM Method of roundness measurement

One of the main problems here is the lack of a representative number of sample data points. As will be seen later in the book, a typical roundness analysis will consist of more than 2,000 data points: to take such a number of data points on a conventional probing CMM would take a considerable length of time. Scanning probe CMM's can, of course, perform the task far more quickly.

The other significant drawback of CMM measurement is that each data point has a positional uncertainty in space. For this reason, even if many data points are measured on a CMM, the uncertainty of the roundness result is relatively high compared to the "Rotational Datum Method" (see next section). However, a CMM will give an absolute diameter measurement, whereas the rotational method only measures out-of-roundness.

These methods (vee and CMM) should not be assumed to be a true measurement of roundness, and their use falls outside the guidelines of all mainstream national and international standards of measurement. Their use is limited to components with out-of-roundness tolerances of 10μm and above.

These methods will not be considered further in this book.

Rotational datum method

To properly assess the roundness of good quality components the best reference is a rotational datum. This is the method that will be considered in the remainder of this book. At its simplest, the part to be assessed is placed on a rotary table and the movement of the surface towards or away from a gauge is monitored as the part is rotated. This is shown schematically in **Figure 17**.

Figure 17: Typical roundness instrument uses a precision spindle to assess departures from a true radius

It should be noted that this method cannot measure the absolute diameter of the measured object as the gauge measures the deviation from a perfect circle, and has no diametrical knowledge.

The displacement of the gauge is monitored continuously (or, in a digital world, frequently) and plotted against the angular displacement of the rotary table. As shown in **Figure 18** and **Figure 19** the results can be displayed in both linear and polar formats, with the polar format being more common.

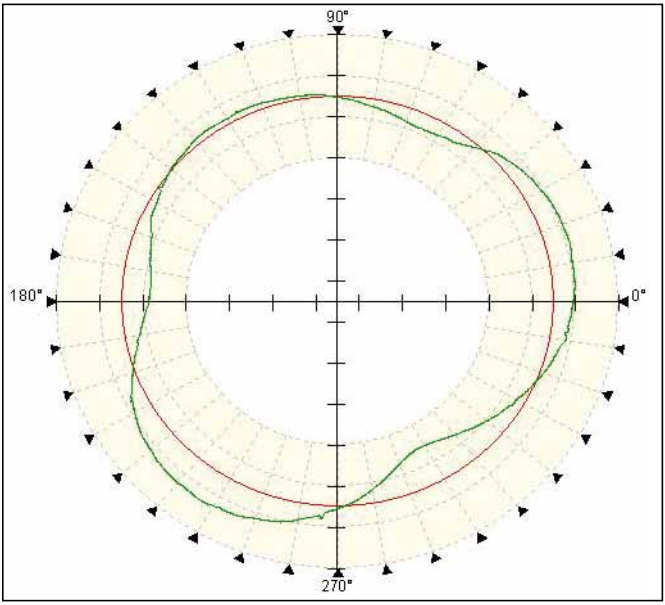


Figure 18: Example of polar plot

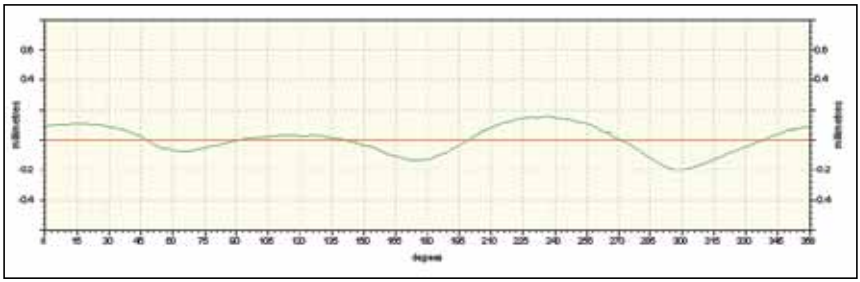
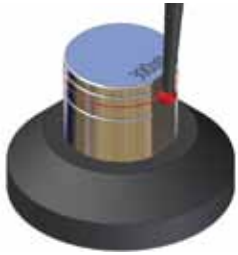


Figure 19: Example of linear plot

One of the first things you will notice about the polar plot is that the sample looks very out-of-round whereas we know that it is actually quite good – certainly of a quality that it would not be possible to see the out-of-roundness with the naked eye. It is important to understand this visualization before we proceed to a more in-depth analysis.

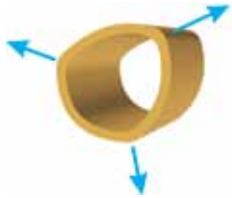
Figure 20 shows two typical parts with different scales on the polar diagram. In plots c) and d) the scaling is such that the out-of-roundness is not evident. Increasing the sensitivity of the scales in e) and f) now shows the magnified deviations from roundness. Note that the form of the component appears distorted. Increasing the scale further plots g) and h) show an even more distorted view of the part, i.e. the flat appears to be a parabola.

Flick Standard



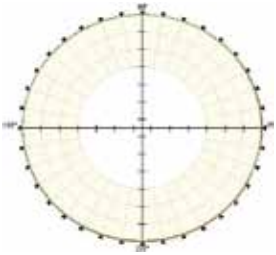
a) Picture of part

Tri-lobed part

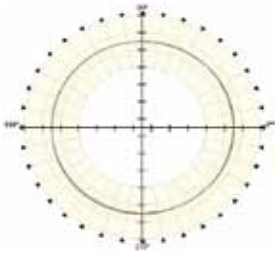


When part is released from the chuck the shape changes slightly due to the release of stress caused by overtight jaws

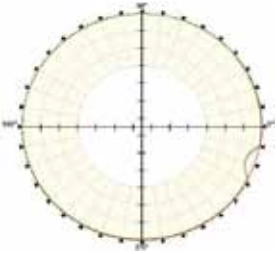
b) Picture of part



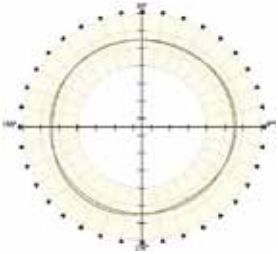
c) 1:1 scaling (10 mm/div)



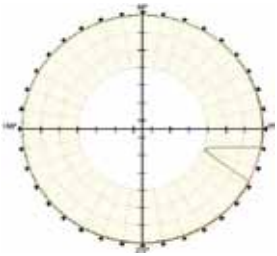
d) 1:1 scaling (10 mm/div



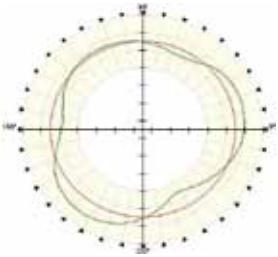
e) 100µm/div



f) 100µm/div



g) 1µm/div



h) 1µm/div

Figure 20: Effects of scaling changes on visual display

Chapter 4 - Putting a number to it

So far in this book we have referred to "out-of-roundness" without being specific about its definition: it is time to tackle that omission. Firstly, it is important to note that the term "roundness" is often used in place of the more descriptive "out-of-roundness". From this point forward the term "roundness" will be used

Reference circles (Figures appear on page 26)

Roundness definitions are based on deviations from a reference circle: therefore the first step in "putting a number to it" is to define that reference. Historically, the roundness value was calculated by placing a template over the profile and centralizing the profile visually. The highest peak and the deepest valley were then identified and the difference between the two calculated. The procedure was operator dependent and the accuracy therefore could suffer from personal opinion and operator skill level. Modern computing methods remove operator interpretation (and the potential errors associated with such methods) by the application of mathematically defined reference circles.

There are four different reference circles specified in the international standards, these are:

(i) **Least Squares Circle (LSCI)** This circle can be regarded as representing the average of all the peaks and valleys (**Figure 24**). The mathematical definition of the circle is that "the sum of the squares of the radial distances measured from the reference circle to the profile has minimum value". The center is referred to as the Least Squares Center.

Because the Least Squares Circle is effectively derived as an "average", its center and radius are very stable and so it is the most commonly used reference.

(ii) **Minimum Zone Circles (MZCI)** These are two concentric circles which just enclose the profile and which have minimum radial separation (**Figure 25**). The center is termed the Minimum Zone Center.

This reference circle should give the lowest value of roundness of any of the reference circles.

Often a third circle is defined, which is the Mean Minimum Zone reference circle. This is simply the mean of the two minimum zone reference circles. It is a useful construct as deviations can be measured from this profile in a way that is analogous to measuring from the least squares reference circle.

(iii) **Maximum Inscribed Circle (MICI)** This is the largest circle that can be drawn completely inside the profile, without cutting it (**Figure 26**).

The Maximum Inscribed Circle is not necessarily a unique solution. On a part with perfect lobing the center of the circle could shift significantly and yet still achieve the same minimum roundness value at each of these positions. In reality this rarely happens. This parameter is used to indicate how the part will fit onto a shaft and is typically used when measuring bores.

(iv) **Minimum Circumscribed Circle (MCCI)** This is the smallest circle that will completely enclose the profile without cutting it (**Figure 27**). This reference is often used to indicate how well the workpiece will fit into a bore and is typically used for the measurement of shafts.

The inscribed and circumscribed circles are sometimes termed the plug gauge and ring gauge circles respectively because they simulate the use of these gauges in checking a bore or shaft. The terms, however, could be criticized because checking with a gauge is essentially a three-dimensional check, whereas a profile represents a two-dimensional cross-section only.

The polar chart

The most obvious way of presenting roundness data is to use a polar chart. Before presenting diagrams that show the different reference circles, there is an important feature of the polar chart that needs to be discussed – scaling. Many readers are probably familiar with Cartesian graphs that have different scaling in the X and Y directions and a false offset.

These constructs are used to highlight the detail in the data. An example is shown in **Figure 21** and **Figure 22** on page 24. In **Figure 21** it looks as though the values are constant, whereas in **Figure 22** the variations and trend can be clearly seen. This is because the data has been drawn from a false offset (99935000) instead of 0 and as a consequence a higher magnification has been used for the Y-axis. The offset has been taken as a number just smaller than the minimum value in the data.

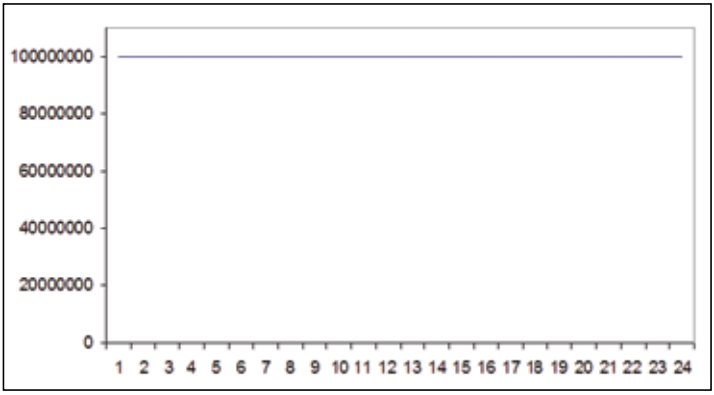


Figure 21: Data presented without the use of an offset. The trend appears horizontal.

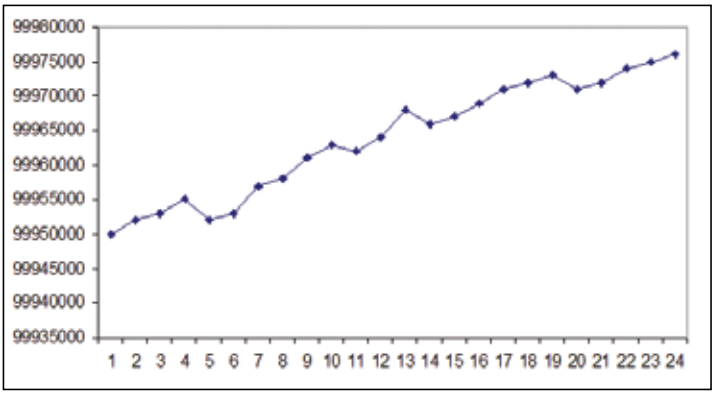


Figure 22: Same data presented with an offset and re-scaling. The upward trend in the data is now clearly visible.

In the case of polar data, the axes are radial and angular. The angular axis is fixed at 360 degrees. The radial axis is used to show deviations from the reference circle. Because the radial deviations will be several orders of magnitude smaller than the average radius, it is necessary to remove an "offset" and then scale the radial deviations to make them visible. The offset in this case is just smaller than the minimum radial distance from the reference circle center.

One consequence of removing the radius is that this can introduce curvature into the plot. It is important to recognize that this curvature may not be present on the component itself. An excellent example of this is to consider a polar chart resulting from the measurement of a flick standard (a very round component with a flat of known depth ground into it). As can be seen in **Figure 23** the flat appears as a parabola after removal of the radial offset and application of appropriate scaling

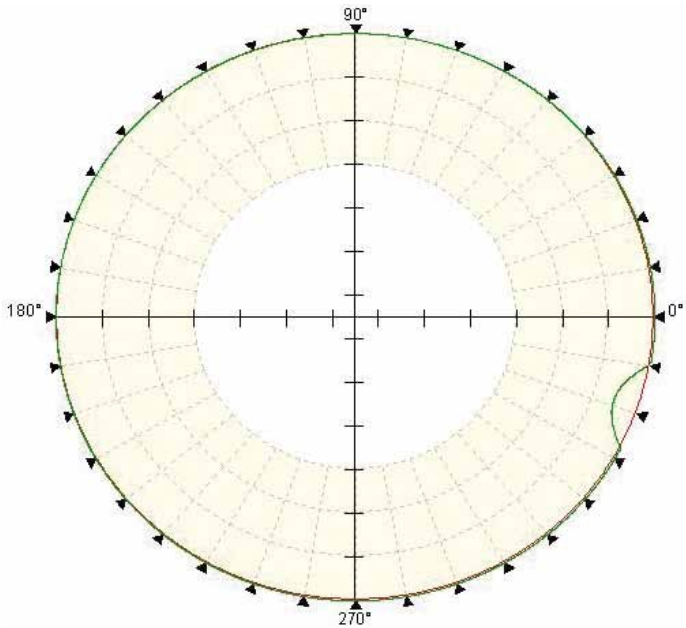


Figure 23: Polar chart of a flick standard

Reference circles – visualization

Having discussed the main concepts of the polar chart, the following figures show how these reference circles would appear on such charts. It should be noted that the data and radial scaling are the same for each of these charts. The apparent change in size of the data in the charts is a result of the removal of different radial "offsets", which arises because of the different radii that are calculated for the different reference circle fits.

One final comment is that in each case the polar chart is centered on the center of the reference circle. This is typical of modern digital systems and has the advantage of displaying the radial deviations in the data at the maximum possible magnification. Older analogue systems used electromechanical chart recorders linked to analogue amplifiers. The consequence of this was that the chart was centered on the rotational axis of the measurement system. Above a certain eccentricity it was necessary to reduce the amplifier gain in order to keep the profile on the chart. If the eccentricity was too great, then a further distortion would be seen in the profile.

In the following figures, "P" represents a peak (outward deviation of the workpiece material) and "V" represents a valley (deviation into the material of the workpiece).

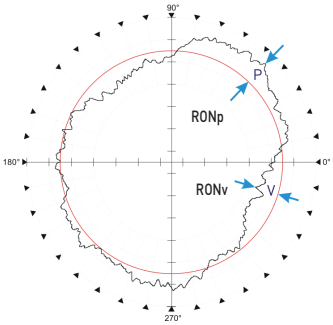


Figure 24: Least squares reference circle (LSCI)

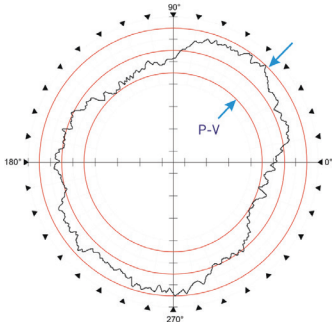


Figure 25: Minimum zone reference circles (MZCI)

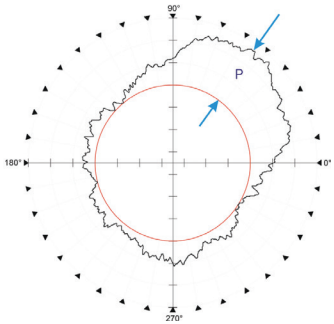


Figure 26: Maximum inscribed reference circle (MICI)

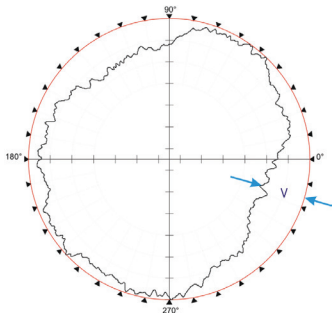


Figure 27: Minimum circumscribed reference circle (MCCI)

Parameters

Roundness parameters are defined in ISO 12181-1 (2003). This standard provides definitions for the assessment of roundness. However, roundness and associated parameters are specified on drawings according to ISO 1101. At the time of writing a revision of ISO 1101 is anticipated that will harmonize some of the parameters, their specifications and definitions. In the following notes the definitions reflect current industrial practice of using the parameters specified in ISO 1101 but with the naming conventions of ISO 12181. Note that some of the parameters defined by ISO 12181 are not discussed because these are not in general use (as they are not specified in the drawing standard ISO 1101).

RONt

Roundness Total (RONt) is the most commonly used parameter. RONt was previously often referred to as "peak-to-valley", and is defined as the separation of two circles concentric with the center of the reference circle that just enclose the data (ISO 1101 – the actual definition in ISO 12181 is slightly different in wording but amounts to the same thing). This parameter is defined for all four reference circles.

RONp and RONv

These two parameters are defined in ISO 12181 for the LS reference circle only. They represent the peak roundness departure (maximum material departure from the fitted reference) and the valley roundness departure (maximum departure from the reference circle into the material of the workpiece). When relating these parameters to a roundness plot, it is therefore necessary to know whether the measurement is of a bore or a shaft, as this will change the air/material relationship.

Other ISO parameters (Runout, Concentricity)

There are a number of other parameters that are strongly related to roundness that also need to be understood in order to make best use of an instrument's analysis capability.

Runout

Runout is always defined with respect to a datum, and is the difference between the nearest and furthest point on a profile from the datum (note that no reference circle needs to be fitted). Runout reflects the deflection of a dial gauge held against the part while it is rotated on centers (as shown in **Figure 15**). In ISO 1101 runout is defined as the radial separation of two circles concentric with the datum that just enclose the data.

Note that the definitions of runout and RONt are quite similar. The difference between these two parameters is that RONt is measured from the reference circle center, whereas runout is measured from the datum point.

Concentricity

Concentricity is a measure of the displacement between the reference circle center and the datum. It is defined (in ISO 1101) as the diameter of a circle concentric with the datum that just encloses the center of the reference circle.

Non-ISO parameters (Ecc, DFTC, Slope)

Ecc

Eccentricity is the distance (Ecc) and direction (Ecc Pos) from the reference datum to the center of the fitted reference circle. It is readily seen that the magnitude of the eccentricity is half of the concentricity (**Conc = 2 x Ecc**). Whilst Eccentricity is not an ISO parameter, it is often useful in practical measurement situations, particularly when setting up a measurement.

DFTC

Departure from True Circularity is a parameter that was developed primarily for bearings applications. It is a measure of the radial departure within a user-defined angular window. The window is scanned through a full 360 degrees and the radial departure from the reference center is calculated for each window position. The maximum radial departure is reported as the DFTC together with the angle at which this occurs (DFTC Pos).

Slope

Like DFTC, Slope is a parameter that was originally developed for the bearings industry. It is a measure of how rapidly the measured profile is changing. Slope is calculated by finding the absolute value of the gradient **dr/d**ϕ (where **r** represents radial departure from the center of the reference circle and ϕ represents angle) at each point in the profile. A user defined angular window is then scanned through the gradient data. At each location of the window, the gradient values within that window are averaged. The maximum of these averages is noted, together with the angle at which this occurs. This value is given as Slope Max, and the position as Slope Pos. Slope Ave is the average of all of the individual slope values.

Results presentation

We have now introduced all the basic elements in the measurement of roundness. How can they be displayed in a concise and complete, yet readable, form? The elements that must be included are:

(i) The roundness measurement itself

(ii) The reference circle

(iii) The calculated parameter results

Sometimes a roundness measurement will be made relative to a datum on the workpiece rather than just the instrument spindle datum. Where this is the case it is useful to indicate how the center of the reference circle relates to the position of the datum. In **Figure 27** the location of the datum is indicated by a red cross with an arrow to the center of the reference circle. Note that this indicates direction only as it is often impractical to show the separation on the same scale as the roundness. Magnitude and direction of the eccentricity can usually be selected in the results presentation as shown below.

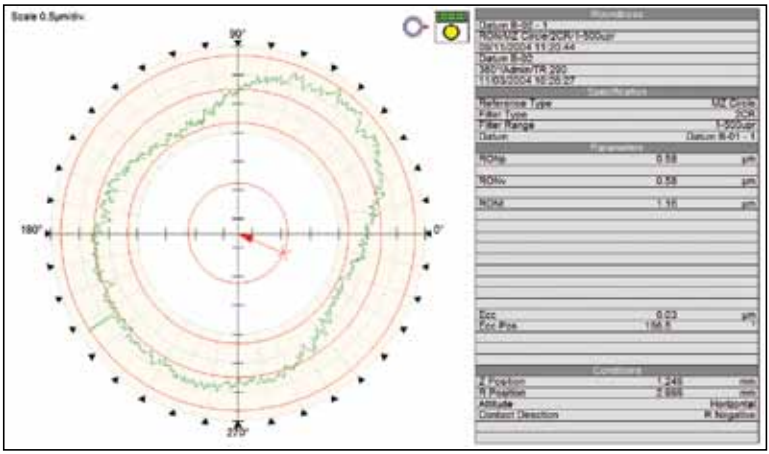


Figure 28: Typical visualization of a Least Squares Reference Circle relative to a workpiece datum

Harmonic Content

Looking at real life roundness plots, it is clear to the eye that information exists in the data at different "frequencies". For instance, in the above example there is evidently an ovality to the workpiece, indicating an irregularity that occurs two times in one complete revolution. There is also a much faster variation in the trace where the irregularities occur in much higher numbers per revolution.

These different frequencies of imperfections are known as "harmonics". The frequency of a harmonic is expressed in "undulations per revolution" or upr, which is the number of waves (peak and valley) caused by that particular aspect of the surface as the part is rotated about its center. For example if the part shown in **Figure 28** were rotated about its center, then the ovality would give rise to 2 undulations per revolution (2 upr), whereas the higher frequency variation would give rise to 100upr or more. Clearly the deviation caused by the ovality would be much greater than that caused by the higher frequency. Using mathematical techniques (known as Fourier Transforms) it is possible to determine the amplitudes of each harmonic within a profile. One convenient way of showing the harmonics is to present them on a histogram showing their relative amplitudes

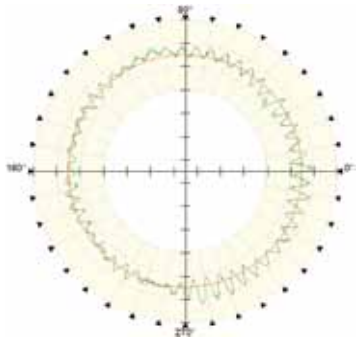
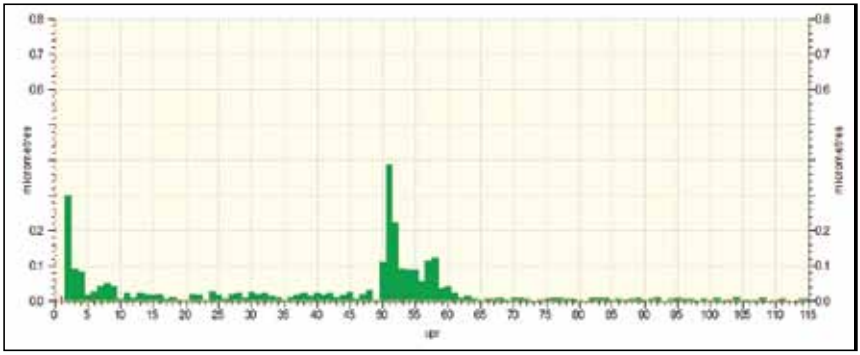


Figure 29: Roundness profile with corresponding harmonic histogram



In **Figure 29** above, a roundness profile is shown that exhibits both an ovality and a higher frequency component. The higher frequency component exhibits a rise and fall in amplitude, which is typically caused by "beating" of closely spaced harmonics. The higher frequency appears on inspection to be at about 50upr. In the corresponding histogram, the amplitude of the ovality can be read off easily. It is clear that the higher frequency component consists of a small group of frequencies just above 50upr.

Another way of representing the harmonic data is to show tables of the harmonic amplitudes and their respective phases. Because these tables are very large, they are not shown here.

Significance of the harmonics

Harmonic analysis is very useful in determining the cause of manufacturing problems, as different issues tend to give rise to different harmonics. Roughly speaking the primary cause of low frequency errors is usually down to component setup errors or machining system errors such as vibration. Higher frequencies are caused by the interactions between the component and the cutting tool. The likely causes of different harmonics are summarized in the table on page 31.

Harmonic range (upr)	Primary Causes
1 upr	Measurement set up error e.g. eccentricity of workpiece to spindle datum
2 upr	Measurement set up error or machining error e.g. tilt of workpiece to spindle datum or machined out of square
3 – 7 upr	Workpiece clamping or manufacturing process e.g. 3 jaw chucking or centerless grinding
8 – 15 upr	Instability of machining process e.g. worn or loose bearings
16 upr upwards	Reaction between materials, machine vibrations e.g. tool chatter

Table 1: Primary causes of harmonic content

Function

Often when making a roundness assessment a particular range of frequencies will be of interest. This range (or "band") of frequencies can be examined in the harmonic histogram or tables. Prior to the introduction of computers in roundness measuring instruments it was not possible to obtain the harmonic data by Fourier analysis. The bandwidth of the data then had to be limited to the frequencies of interest by means of filters. Originally roundness instruments used filters based on circuits using a combination of capacitors and resistors – the so-called 2CR filter. These days the filters are applied numerically by means of special filter algorithms implemented within a computer, but the principles are the same.

Unlike the harmonic analysis approach, a filter does not simply block off all of the unwanted frequencies and let through all the wanted frequencies but rather it attenuates the frequencies. The degree of attenuation at any frequency is defined by the transmission characteristic of the filter. There are two commonly used filters – the 2CR filter (or a variant known as the Phase Corrected 2CR filter) and the Gaussian filter. The transmission characteristics are very different for these two filters as shown below. For clarity only the low-pass characteristics are shown

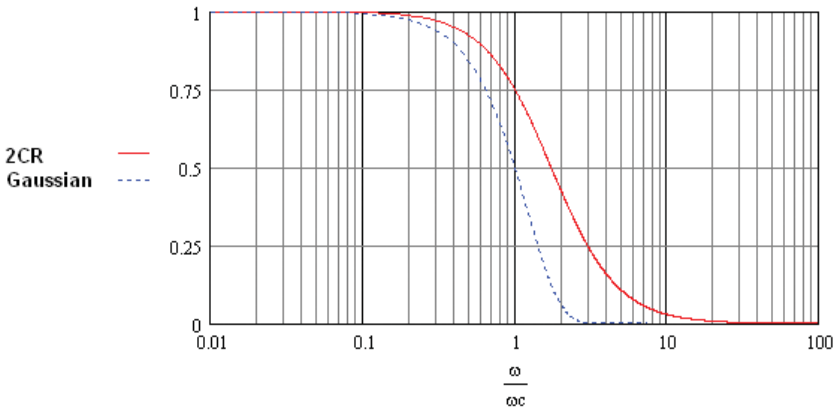


Figure 30: Transmission curves for the 2CR and Gaussian low-pass filters as a function of normalized frequency (ω/ωc)

Some important points that should be noted are:

(i) The filter is defined by its "type", "cut-off" and the percentage transmission at the cut-off.

(ii) For a 2CR filter the transmission is 75% at the cut-off. For a Gaussian filter the transmission is 50% at the cut-off.

(iii) Close to the cut-off frequency both filters will attenuate "wanted" frequencies as well as "unwanted" frequencies. The Gaussian filter attenuates the "wanted" frequencies much more than the 2CR filter.

(iv) The "roll-off" of the transmission characteristic of the Gaussian filter is much steeper than that of the 2CR filter. This means that the Gaussian filter is very much better at suppressing unwanted frequencies.

In the above example a low-pass filter has been shown. For roundness instruments the equivalent high-pass filter (rejects low frequencies) is constructed differently for the 2CR and Gaussian cases. In the case of the 2CR filter, the filter function is the mirror image of the low-pass filter. However for the Gaussian filter the transmission of the high-pass filter is 1 – transmission of the low-pass filter.

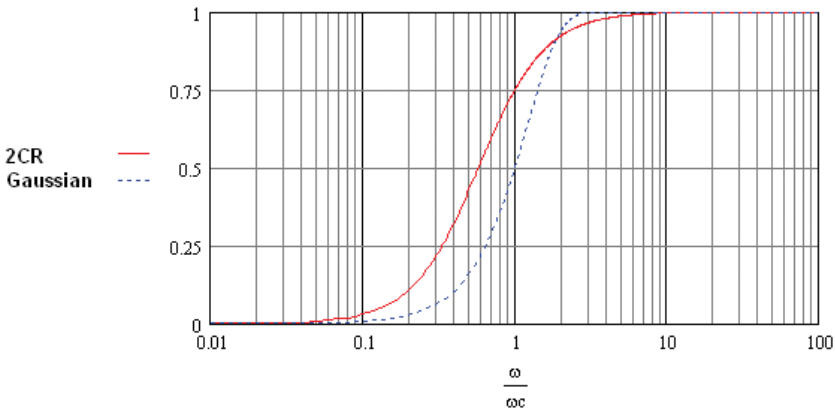


Figure 31: Transmission curves for the 2CR and Gaussian high-pass filters as a function of normalized frequency (ω/ωc)

Sometimes a band-pass filter is used to select a band of frequencies that do not include the very low frequencies. These filters are "constructed" by applying a low-pass and a high-pass filter.

Specifying a filter bandwidth

Roundness filters are specified by specifying the type of filter (e.g. Gaussian or 2CR) and the bandwidth. A band-pass filter that suppresses frequencies below 15upr and above 50upr is specified simply as a 15-50upr filter. A peculiarity exists when specifying a simple low-pass filter (the most common type of filter used). In this case the lower cut-off is always shown as 1. This means that a low-pass filter that suppresses frequencies above 50upr is specified as a 1-50upr filter. This is a little bit strange at first because a low pass filter in other disciplines would be specified as 0-15upr, but the reader needs to be familiar with this convention.

Standard ISO filter selections

When filters were implemented by means of electronic circuits, there were only a limited number of filters that were available for selection. The international standards settled on having filter cut-offs at 15, 50, 150 and 500upr. This sequence can be extended to 1500 or 5000upr etc. The bandwidth of any standard filter is selected by choosing a lower frequency cut-off and a higher frequency cut-off out of this list. For low-pass filters a selection of "1" is allowed as discussed above. Nowadays software will often allow the user a free choice of the lower and upper cut-offs, so a bandwidth of say 17-38upr is possible. The results of applying several different filter bandwidths to a surface are shown in **Figure 32** to **Figure 36**.

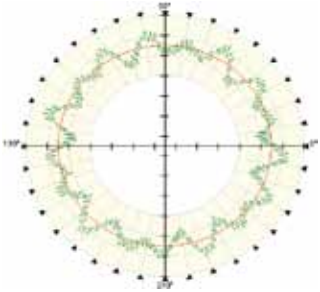


Figure 32: No Filter

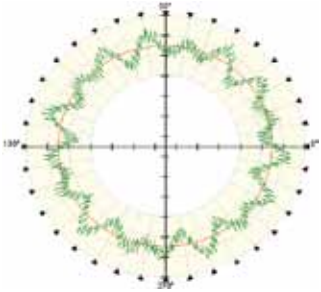


Figure 33: 1-500upr filter

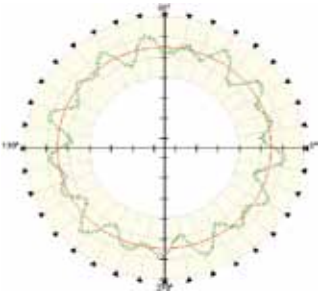


Figure 34: 1- 150upr filter

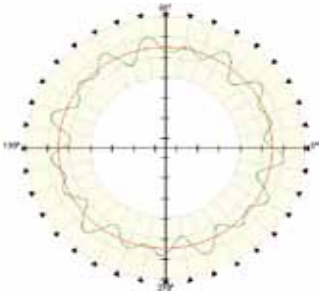


Figure 35: 1-50upr filter

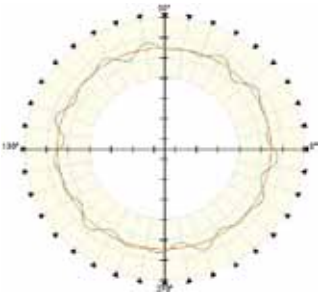


Figure 36: 1-15upr filter

Filter run-ups

It is important to note that data measured on a roundness instrument might have gaps or "interruptions" in it. The data presented above has no such gaps or "interruptions". Where there are gaps, there is an issue to be resolved whenever a filter is applied. This arises because the filter needs a certain amount of data to be processed before stable filtered data is available. The amount of data is called a "run-up". Run-ups need to be dealt with on either side of any interruption.

It is important to note that on roundness instruments the rejection of data in the run-up area is not always done automatically. Usually the software will provide one or more methods for handling data within the run-up areas. Users should familiarize themselves with these features to ensure that the data is dealt with appropriately prior to parameter calculation.

Filter cut-off and component diameter

Although roundness is independent of size it is useful to consider the relationship between filter bandwidth, surface wavelength and component diameter. Very simply, a component of diameter **D** mm has a circumference of **πD** mm; this equates to 1upr. In other words a frequency component of 1upr has a wavelength of **πD** mm. At the higher cut-off, **F** the wavelength on the surface corresponding to this frequency will be **πD/F** mm.

As an example, a 500upr wave on a 300mm diameter component will have a wavelength of about 2mm. A wave of this wavelength might well represent tool chatter. By comparison a 500upr wave on a 10mm diameter component will have a wavelength of about 60µm. This represents surface finish that is likely to arise from the cutting process. In addition, because the stylus used for measuring the component is likely to have a radius of the order of 1mm, this wavelength may well be heavily suppressed anyway. For this reason, when considering the choice of filters, it is necessary to bear in mind:

(i) What it is that you are trying to assess (chatter, lobing etc – this determines the wavelengths of interest)

(ii) The size of the component

(iii) The size of the stylus tip radius

Chapter 5 - The whole geometry of a workpiece

An extremely large number of components used in engineering are basically cylindrical. These components range from spindles for watch components to large engine components such as crankshafts, which are composed of a number of cylindrical sections. In such components, roundness is only one aspect that we need to measure in order to control the manufacturing process. Other aspects include flatness, squareness, straightness and cylindricity, all of which can be measured on suitably equipped roundness systems. A typical example of such a system is the Talyrond instrument shown below.

1. Vertical straightness datum
2. Centering and levelling table
3. Spindle
4. Radial straightness datum
5. Articulating gauge holder
6. Stylus

Figure 37: Fully automated precision roundness and form measuring instrument

For a measuring instrument to be able to measure all of these features, it is necessary to combine the spindle with high precision linear axes (for radial and vertical movement and measurement) and to combine all of these in a highly stable structure so that their relative positions are maintained. Facilities need to be provided to enable the component axis to be accurately aligned to the spindle axis and to allow the gauge to be moved into different attitudes (vertical and horizontal) and orientations to be able to address the different types of features.

The Talyrond instrument shown provides all of these facilities. For example the precision centering and levelling table enables components to be centered automatically to better than 1µm from the true spindle axis. The gauge support structure provides for automated changes of both attitude and orientation enabling the gauge to be positioned to measure roundness or straightness inside a bore or on the external surface of a shaft, or to measure flatness or straightness on either the upper or lower surfaces of a flange.

Having already discussed roundness in detail, the other fundamental measurement types (flatness and straightness) and their parameters are discussed below. In addition some of the more common parameters that can be obtained by combining more than one measurement (cylindricity, multi-plane flatness) or relating one measurement type to another (squareness, parallelism, coaxiality) are also presented. Other specialist assessments that combine multiple measurements, such as cylindrical mapping, are discussed later in the book.

Cylindricity

By now, the reader should be familiar with the concept of roundness as measured by the rotating datum method, the presentation of results, the key parameters of roundness and the basics of harmonic content. Although the assessment of roundness provides a powerful analysis tool for high quality rotationally symmetric parts, it suffers from a key limitation: it is only a 2 dimensional analysis of a 3 dimensional part. While a single trace is a good indicator of the quality of a part, important features affecting performance can be missed when only one measurement is taken.

A better analysis can be made by taking a number of roundness measurements at intervals along the axis of the component and then combining these into a cylinder.

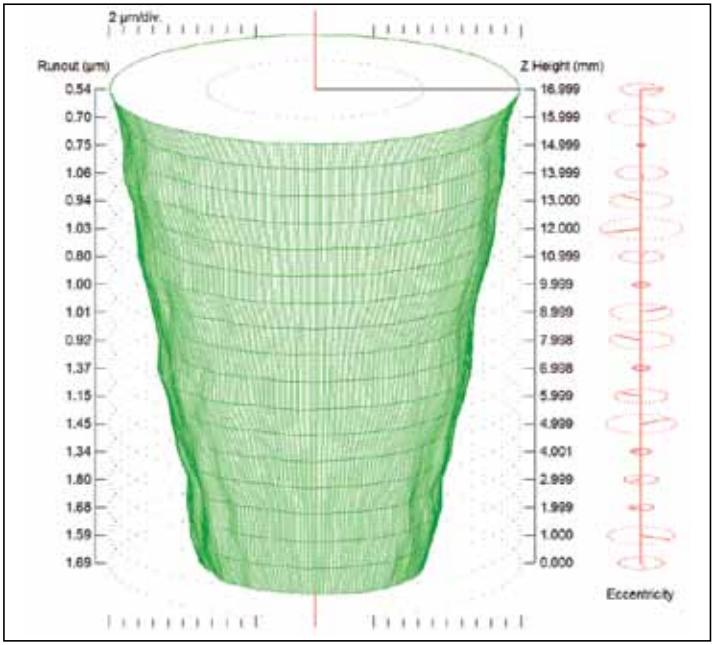


Figure 38: Example cylindricity result

Figure 38 above shows the result of 18 roundness measurements made over the length of a part. Computer graphics have been used to display the results, which can be made to rotate on-screen, helping in visualization of anomalies.

Measurement Method

Cylindricity is normally assessed by combining a number of roundness measurements taken at different heights on the component. In the simplest instruments this movement is provided manually. In more sophisticated instruments the movement of the gauge can be motorized to facilitate more precise positioning and movement under computer control. With either method it is mandatory that the gauge not lose contact with the component.

The key requirement in the measurement of cylindricity is that the gauge movement must be precisely vertical and parallel to the axis of rotation of the rotary datum. It is therefore necessary to have a vertical datum with an axis that is both straight and parallel to the rotational datum. Typically (but not essentially) such a vertical datum element also provides a straightness measuring capability and is often termed a Vertical Straightness Unit (VSU).

Once the data has been acquired, variations of the data from a true cylinder can then be calculated in an analogous way to the analysis of roundness

Reference Cylinders

The quantity to be calculated is "cylindricity" (CYLt), which is a measure of the deviation from a true cylinder. As with the single roundness trace, cylindricity requires the fitting of reference forms, this time cylinders instead of circles. Cylindricity is then defined as the radial separation of two cylinders coaxial to the reference cylinder that just enclose the data.

There are four reference cylinders. They are:

(i) **Least Squares Cylinder (LSCY)** This cylinder can be regarded as representing the average of all the peaks and valleys (**Figure 39**). The mathematical definition is that "the sum of the squares of the radial distances, measured from the reference cylinder to the profile, has minimum value".

The Least Squares Cylinder is the most stable reference cylinder and hence it is the most commonly used. Importantly it is this axis that is used when centering and levelling a component to the rotational datum. Consideration of the other reference cylinders will reveal that their axes can be swayed by extreme data.

There are three other reference cylinders used, as outlined below. It should be noted that all of these would be swayed by extreme points in the data, such as spikes that may represent contamination of the part or scratches. For this reason they should be used with caution.

(ii) **Minimum Zone Cylinder (MZCY)** These are two cylinders, with a common axis (i.e. coaxial), which have the minimum radial separation required to enclose all points in the profiles (**Figure 40**).

This reference cylinder should give the lowest value of cylindricity of any of the reference cylinders and is often the preferred method of analysis in many company and international standards.

(iii) **Maximum Inscribed Cylinder (MICY)** This is the largest cylinder that can be drawn completely inside the profiles (**Figure 41**).

(iv) **Minimum Circumscribed Cylinder (MCCY)** This is the smallest cylinder that will completely enclose all the measured points (**Figure 42**).

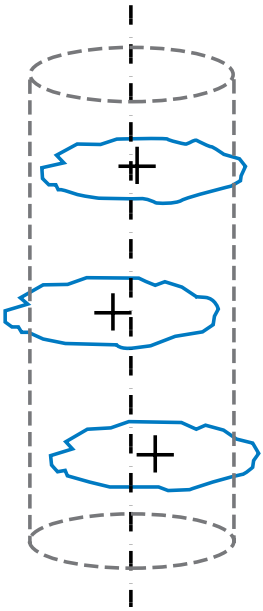


Figure 39: Least Squares Cylinder

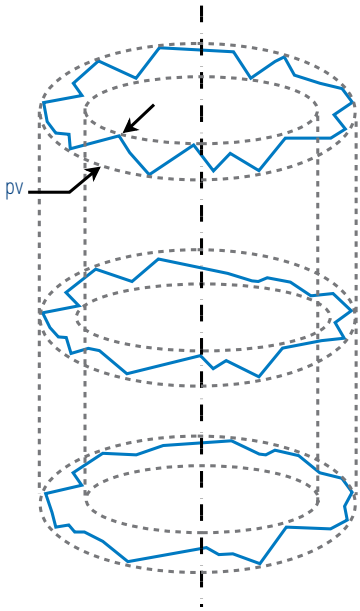


Figure 40: Minimum Zone Cylinder

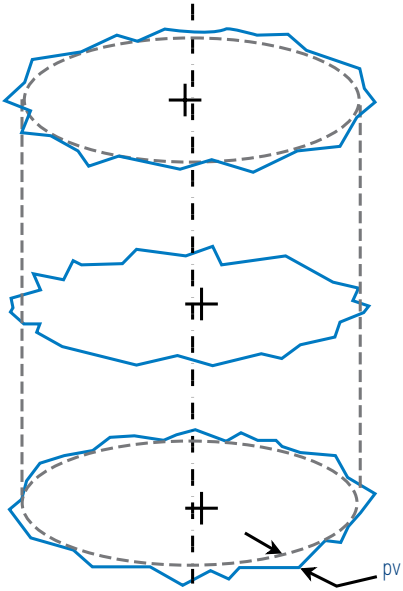


Figure 41: Maximum Inscribed Cylinder

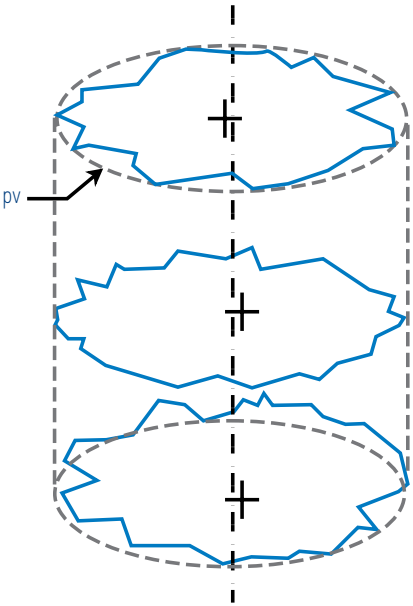


Figure 42: Minimum Circumscribed Cylinder

Cylindricity Parameters

Cylindricity parameters are defined in [ISO 12180-1]. This standard provides definitions for the assessment of cylindricity. However, cylindricity and associated parameters are specified on drawings using ISO 1101. At the time of writing a revision of ISO 1101 is anticipated that will harmonize some of the parameters, their specifications and definitions. In the following notes the definitions reflect current industrial practice of using the parameters specified in ISO 1101 but with the naming conventions of ISO 12181. Note that some of the parameters defined by ISO 12180 are not discussed because these are not in general use (as they are not specified in the drawing standard ISO 1101).

CYLt

Cylindricity (CYLt) is the most commonly used parameter. CYLt was previously often referred to as "peak-to-valley", and is defined as the separation of two cylinders coaxial with the axis of the reference cylinder that just enclose the data (ISO 1101 – the actual definition in ISO 12180 is slightly different in wording but amounts to the same thing). This parameter is defined for all four reference cylinders.

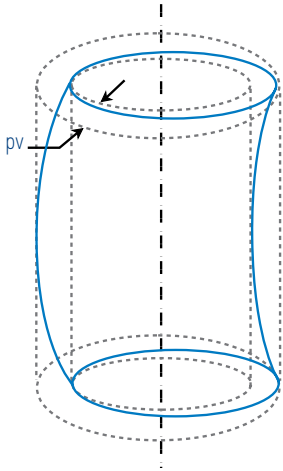


Figure 43: Illustration of cylindricity tolerance

CYLp and CYLv

These two parameters are defined in ISO 12180 for the LS reference cylinder only. They represent the peak maximum material departure from the fitted reference (CYLp) and the valley maximum departure from the reference cylinder into the material of the workpiece (CYLv). When relating these parameters to a cylindricity plot, it is therefore necessary to know whether the measurement is of a bore or a shaft, as this will change the air/material relationship.

Other ISO parameters (Taper, Runout, Coaxiality)

There are a number of other parameters that are strongly related to cylindricity that also need to be understood in order to make best use of an instrument's analysis capability.

CYLtt

Cylinder Taper (CYLtt) reflects the taper in the component. In common industrial practice this parameter is calculated as follows. For each angle 0° to 180° a straight line is constructed through the data point corresponding to that angle in each roundness plane in the cylinder. Another straight line is constructed through the points diametrically opposite to these points. The local cylinder taper is calculated as the absolute difference in diameters measured between these straight lines at the top and bottom of the cylinder. CYLtt is calculated as the maximum of all of these local taper values.

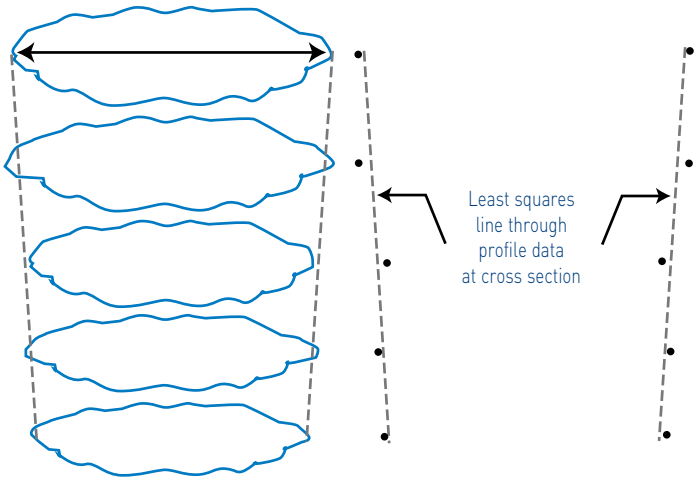


Figure 44: Derivation of CYLtt - Maximum Cylinder Taper

Note, in the published ISO standard, CYLtt is defined as half of the above figure and is valid only for the LSCY reference. It is therefore important to know which version of the parameter is being referred to in the drawing and which version is being calculated by the measuring instrument software.

It should be noted that the units of CYLtt are length, not angle; therefore the parameter is sensitive to the length over which the measurement is made.

It is common in instrument software to show CYLtt as a signed value, indicating whether the component tapers in or out at the top.

Whilst the CYLtt parameter and the display of cylindricity show something of the taper of a component, the data density in the axial direction is very limited. If a more in-depth analysis of the form of the cylinder in the axial direction is required, then this can be accomplished by straightness and parallelism assessments as described later.

Total radial runout

As with cylindricity, total radial runout is always defined with respect to a datum. Total radial runout of a cylinder is determined as the difference in the radial distances, measured from the datum axis, to the furthest point and nearest point in the data. Runout reflects the deflection of a dial gauge held against the part while it is rotated on centers (as shown in **Figure 15** on page 17).

In ISO 1101 total radial runout is defined as the radial separation of two cylinders coaxial with the datum axis that just enclose the data. Note that the definitions of Total Radial Runout and CYLt are quite similar. The difference between these two parameters is that CYLt is measured from the reference circle center, whereas runout is measured from the datum point.

Coax

Coaxiality (Coax) is a measure of the displacement between the reference cylinder axis and the datum axis. It is defined (in ISO 1101) as the diameter of a cylinder whose axis is defined by the datum axis and that just encloses the axis of the reference cylinder. There are two common interpretations as to how to find this value. In the first interpretation it is the imaginary line that represents the axis of the reference cylinder that is used.

In the second interpretation it is the centers of the individual planes of the test cylinder that are used to find the coaxiality. In other words, in this second definition the coaxiality is equal to the maximum concentricity with the datum axis of any plane in the test cylinder. These two definitions are sometimes referred to as Coax (ISO) and Coax (DIN) as the second definition was most commonly used in Germany.

In both cases the test axis is deemed to be restricted in space by the positions of the upper and lower planes used to define the axis.

Coaxiality is normally calculated between two cylinder axes, however this is not essential. As coaxiality relies only on the centers of roundness planes, even a simple roundness instrument without a vertical straightness datum can be used to measure coaxiality.

Filtering

The previous discussion on the filtering of roundness data applies to cylindricity. The same filter must be applied to all the planes that are used to construct the cylinder.

Straightness

Cylindricity considerably improves our knowledge of the overall form errors of the component. However, although a large number of planes could be taken, the amount of data measured along the surface is usually very limited. This can be augmented by taking a straightness measurement. The straightness results can also be supplemented by taking additional measurements and combining them to form a parallelism analysis. These two topics are discussed below.

Straightness is measured with the pick-up traversing along (up, down or across), instead of around, the surface. Measurements are made relative to the line of traverse, which is normally either parallel to the roundness axis of rotation (vertical straightness) or normal to it (horizontal straightness).

Reference Lines

There are two reference lines that can be applied to straightness, these are:

(i) **Least Squares Straight Line (LSSL)** This reference can be regarded as representing the average of all the peaks and valleys. The mathematical definition is that "the sum of the squares of all the distances measured from the reference line to the data has minimum value".

(ii) **Minimum Zone Straight Line (MZSL)** This is defined as a pair of lines separated by the minimum distance necessary to just enclose the data. As with roundness a third line (the mean of these two lines) is defined. This mean minimum zone straight line is useful as it provides a reference from which to measure deviations in an analogous way to the LSSL.

Straightness Parameters

STRt

Straightness total (STRt) is defined in ISO 1101 as the separation of two lines parallel to the reference axis that just enclose the data.

Runout

As with roundness, runout is measured from a datum. Typically that datum is a straight line from another straightness measurement or from a computed axis such as a cylinder axis. Runout is defined in ISO 1101 as the separation of two lines parallel to the datum that just enclose the data.

Filters

It is often useful to suppress short wavelength variations in the data such as noise or machining marks so as to be able to visualize the underlying straightness more clearly. This is accomplished by means of filters. In the case of straightness low-pass filters are used to suppress the shorter wavelengths (higher frequencies) that are seen in the profile. As with roundness there are two types of filters that are commonly used, the 2CR and Gaussian filters. The transmission characteristics for these filters are shown in **Figure 30** on page 32. Instead of being specified in terms of a frequency, these filters are specified in terms of a wavelength (or cut-off length). The cut-off that is selected is normally chosen from a standard set of cut-offs:

0.25mm 0.8mm 2.5mm 8mm 25mm

The choice will be limited by the length of the data itself. When applying filters it should be borne in mind that data within one cut-off of either side of any interruption (including the ends of the data) will be severely affected by "run-up" effects. This data should be discarded when considering the straightness analysis.

PAR

Parallelism (PAR) can be calculated based on two vertical straightness measurements taken at diametrically opposed positions on the component. One measurement is chosen as the datum, and a best-fit line (least squares or minimum zone) derived. Both straightness data sets are then rotated so that the datum is vertical. There are two ways of calculating the parallelism between the datum trace and the test trace. The first PAR(D) is to calculate the parallelism of the data contained in the test trace. This value is then the separation between two lines parallel to the datum that just enclose the data. This is equivalent to the runout from the datum.

The second way (PAR) to calculate parallelism is to fit a reference line (LSSL or MZSL) to the test trace and then to calculate parallelism as the separation of two lines parallel to the datum that just enclose the fitted reference line. This is illustrated in **Figure 45**. The units of PAR and PAR(D) are length, not angle; therefore the parameter is sensitive to the length over which the measurement is made. In some software packages the angle between the traces is also shown for convenience.

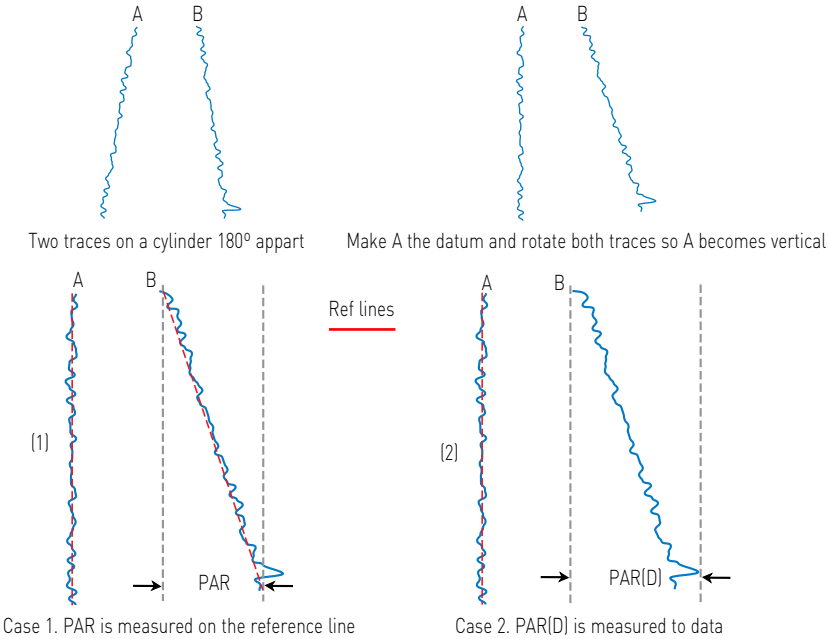


Figure 45: Parallelism calculations

Where a parallelism tolerance is marked on a drawing, then the indication is that if the component is measured at any angular position the parallelism will not exceed the stated figure. Clearly it is impractical to make a large number of parallelism measurements and so a regime that highlights exactly where to make the parallelism measurements is important. One possible regime is to use the position of the CYLtt value to indicate where to make the straightness measurements for the parallelism analysis.

Having made the measurements at these positions, parallelism of one side to the other should be calculated for each side. This is because the two values are typically different, and might indeed be very different in the presence of extremes of data in one trace rather than both. Clearly each of the two values needs to be compared to the specification limit.

Flatness

By rotating the gauge of our roundness instrument so that the measurement plane of the gauge is axial rather than radial, the system can now measure "flatness" as shown below.

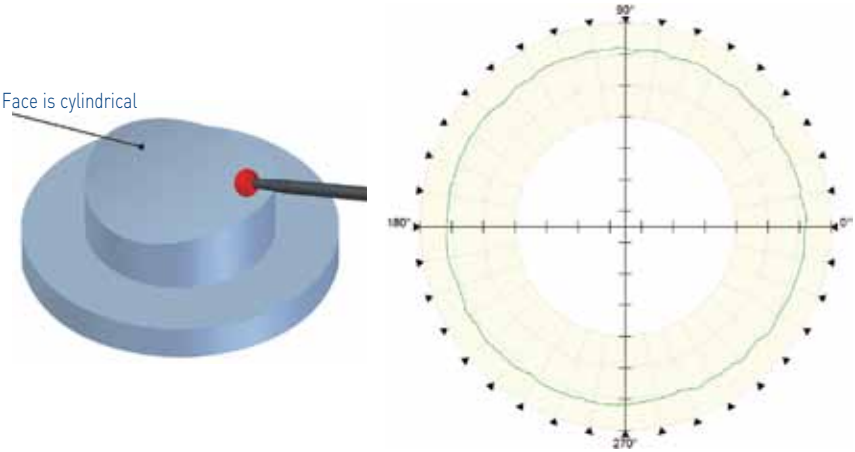


Figure 46: Measuring a horizontal surface exhibiting a cylindrical feature

The interpretation of the polar plot (right hand side of **Figure 46**) is similar to that of a roundness profile, except that radial variations in the trace correspond to physical up-and-down movements of the stylus. With a little practice the reader will soon become comfortable with the representation.

As with roundness, in order to quantify flatness it is necessary to fit a reference form. In this case the reference form is a plane. Two options exist for plane fitting: Least Squares and Minimum Zone. The flatness is then defined as the separation of two planes, parallel to the reference plane, that just enclose the profile.

Clearly, a single flatness trace will reveal a limited amount of information about the complete form of a plane surface. For example making a single flatness measurement on a well-centered ball will show only the variations in height at the radius of measurement. These will be very small, suggesting that the surface is "flat" when clearly it is not! By taking a number of flatness measurements at different radii a much fuller picture can be built up. This extension to the simple flatness measurement is known as "multiplane flatness". In the example given the shape of the ball will now be immediately obvious. Advanced display software allows for 3D representations of multiplane flatness measurements, as shown in **Figure 47**.

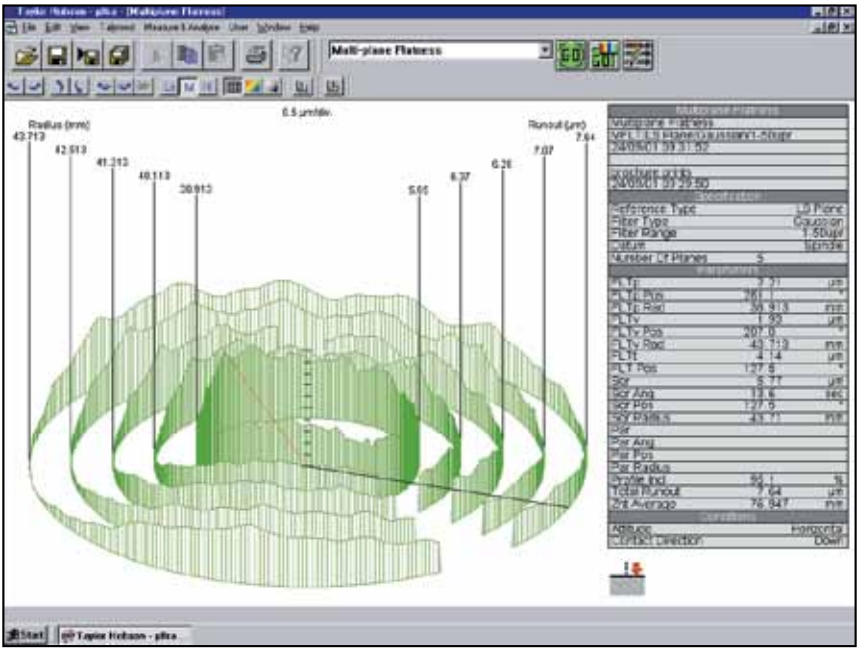


Figure 47: Multiplane flatness result

Closely related to flatness is "squareness": this looks at the angular displacement between a measured flatness plane and a reference axis, as shown in **Figure 48**. The reference axis used might be the spindle axis or a computed axis, such as a cylinder axis.

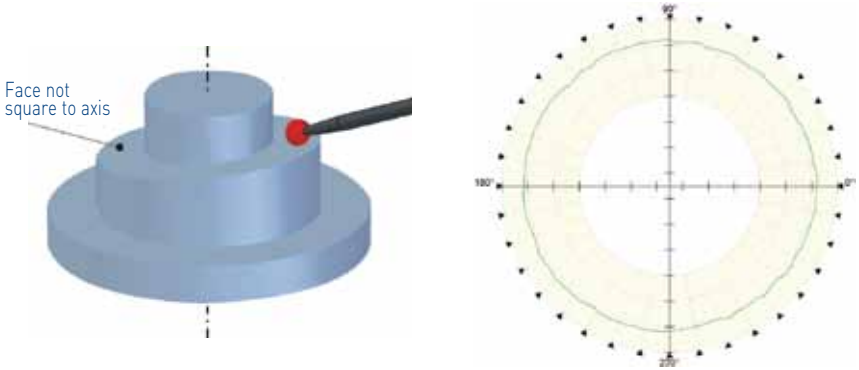


Figure 48: Measuring a horizontal surface exhibiting poor squareness

It is also possible to measure the parallelism between a flatness measurement and a previously calculated plane.

Measurement Method

Single trace flatness measurements can be made with the simplest instrument, provided that the gauge can be re-orientated to measure vertical, rather than horizontal, displacement.

However, to make multiplane flatness measurements, the movement of the gauge must be closely controlled relative to the spindle axis. Of prime importance are the straightness of the horizontal axis and the squareness of the horizontal axis to the spindle axis. Both of these will have a major influence on the ability of an instrument to measure multiplane flatness.

Reference Planes

As previously mentioned there are two reference planes that are commonly fitted:

(i) **Least Squares Plane (LSPL)** This plane is defined such that the sum of the squares of all of the deviations from this plane to the profile points is a minimum.

Because the Least Squares Plane is effectively an "average", it is very stable and as a result is the most commonly used reference plane.

(ii) **Minimum Zone Plane (MZPL)** This reference is defined by two parallel planes that just enclose the data.

It is sometimes useful to refer to a mean minimum zone reference plane, which is simply the mean of these two planes. This allows deviation in the profile to be referred from this plane in a manner analogous to deviations from the LS reference plane.

Flatness Parameters

Flatness parameters are defined in ISO 12781-1. This standard provides definitions for the assessment of flatness. However, as in the case of roundness, these parameters are specified on drawings using ISO 1101. In the following descriptions the nomenclature of ISO 12781 is used for parameter names where those parameters are defined in that standard. As with roundness, some of the parameters defined in the ISO standard are not discussed here as they are not in general use.

FLTt

Flatness total (FLTt) is the most commonly used parameter. FLTt was previously often referred to as "peak-to-valley", and is defined as the separation of two planes parallel to the reference plane that just enclose the profile data. This parameter is defined for both reference planes.

FLTp and FLTv

These two parameters are defined in ISO 12781 for the LS reference only. They represent the peak flatness departure (maximum material departure from the fitted reference) and the valley flatness departure (maximum departure from the reference into the material of the workpiece).

When relating these parameters to a flatness plot, it is therefore necessary to know whether the measurement is of an upper or lower surface, as this will change the air to material relationship.

Other ISO parameters (Runout, Squareness, Parallelism)

There are a number of other parameters that are strongly related to flatness that also need to be understood in order to make best use of an instrument's analysis capability.

Runout

As with roundness, runout is always defined with respect to a datum, and is the difference between the nearest and furthest point on a profile from the datum (note that no reference plane needs to be fitted). Runout reflects the deflection of a dial gauge held against the part while it is rotated about the datum axis. In ISO 1101 runout is defined as the axial separation of two planes perpendicular to the datum axis that just enclose the data.

By comparing this with the definition of FLTt it will be seen that the difference between these two parameters is that FLTt is measured from an axis defined by the reference plane (the axis is defined as being perpendicular to the plane and passing through the zero radius point), whereas runout is measured from the datum axis.

Sqr

Squareness (Sqr) on a roundness instrument is normally measured by establishing a datum axis and then referring a flatness measurement to this axis. The appropriate ISO 1101 definition in this case is identical to runout as defined above. In order to provide additional information rather than duplicating the runout value, squareness is often given as the runout of the reference plane from the datum axis at the measurement radius.

Sometimes this is also given in angular or slope units. This permits a user to extrapolate the value measured at a radius close to the edge of a component to the full radius of the component. This is not possible with the ISO definition of squareness. Users should satisfy themselves as to which version of squareness is given for this parameter.

Par

Parallelism (Par) on a roundness instrument is measured between two flatness measurements. ISO 1101 defines parallelism as the separation of two planes parallel to the original plane that just enclose the data. This of course is the same as the runout from the plane. In order to provide additional information rather than duplicating the runout value, parallelism is often given as the runout of the reference plane from the datum plane at the measurement radius.

Sometimes this is also given in angular or slope units. This permits a user to extrapolate the value measured at a radius close to the edge of a component to the full radius of the component. This is not possible with the ISO definition of parallelism. Users should satisfy themselves as to which version of parallelism is given for this parameter.

Non-ISO parameters (DFTP, Slope)

Two useful parameters are departure from true plane (DFTP) and Slope. These are directly analogous to the DFTC and Slope parameters for roundness.

DFTP

Departure from True Plane (DFTP) is a parameter that was developed primarily for bearings applications. It is a measure of the axial departure within a user-defined angular window. The window is scanned through a full 360 degrees and the axial departure from the reference plane is calculated for each window position. The maximum axial departure is reported as the DFTP together with the angle at which this occurs (DFTC Pos).

Slope

As with DFTP, Slope is a parameter that was originally developed for the bearings industry. It is a measure of how rapidly the measured profile is changing. Slope is calculated by finding the absolute value of the gradient $\mathbf{dz/d\phi}$ (where $\mathbf{z}$ represents axial departure from the reference plane and ϕ represents angle) at each point in the profile.

A user defined angular window is then scanned through the gradient data. At each location of the window, the gradient values within that window are averaged. The maximum of these averages is noted, together with the angle at which this occurs. This value is given as Slope Max, and the position as Slope Pos. The average of all of the individual slope values is also given as Slope Ave.

Whole Geometry

Figure 49 shows some typical imperfections that exist in rotationally symmetric components: some of these may be critical to the performance of the component when in use. For instance, one might want to check: (a) that the two different diameter portions are concentric with one another, (b) that the bore of the tube is co-axial with the outside, (c) that the bore is straight, (d) that the horizontal face is square to the axis, (e) that the shoulders and recess are square to the axis and that the upper and lower faces are parallel.

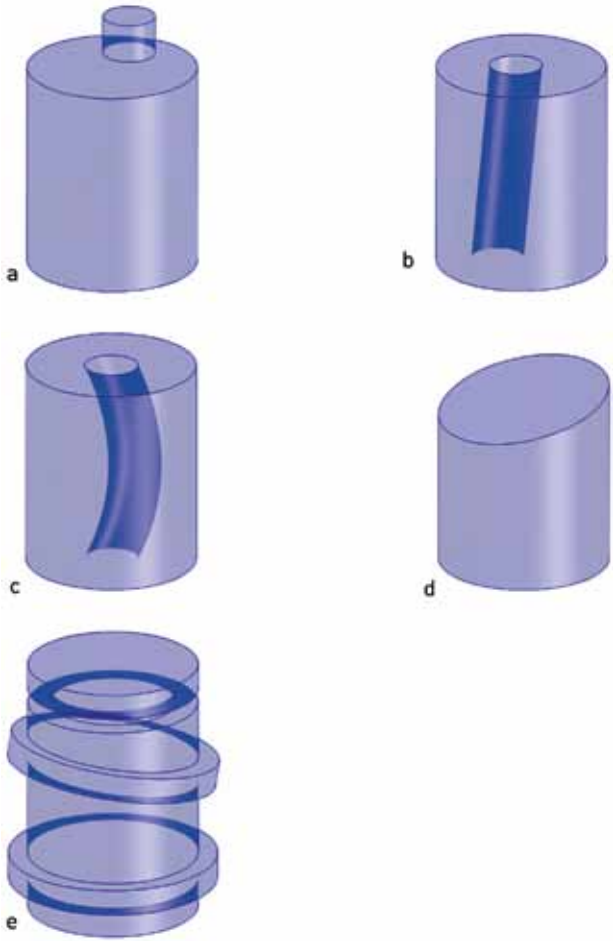


Figure 49: Some errors of form that can be inspected

Harmonic Content and Filtering

Because flatness data is obtained by measurement taken over one revolution of the component, it is again possible to calculate the harmonic content of the data. This is directly analogous to roundness, and the reader is referred to the relevant discussion for further details.

Filters used for flatness data are specified in exactly the same way as for roundness, and again the user is referred to the relevant section above for further details.

Indicating parameters on drawings

In the above discussion, reference has been made to ISO 1101 as the standard that specifies how the various parameters are indicated on component drawings. The ISO symbols used in specifying these parameters are shown in Appendix 2.

Summary

The reader has now been introduced to the basic parameters of roundness, cylindricity, flatness, straightness and squareness. With these parameters and their derivatives, and a fully capable instrument, one can now quantify these imperfections to achieve both process control and pass-fail acceptance tests.

The following chapter describes in detail the principle operating elements of a roundness measuring instrument.

Chapter 6 - Measuring Instruments

In Chapter 3 we introduced the concept of a roundness-measuring instrument with a rotational datum and a gauge. **Figure 50** shows such a device.

1. Manual column and radial arm for gauge positioning
2. Manual gauge attitude and orientation control
3. Rotary table, with manual centering and levelling
4. Gauge

Figure 50: Roundness measurement instrument

In Chapter 5 we added the requirement for vertical and horizontal datums to make an instrument capable of measuring the total form of a rotationally symmetric part (see **Figure 37** on page 36).

In this chapter we will look at each of the essential components of such an instrument, with reference to a modern instrument with computer control and digital electronics.

Gauging

The gauge (often referred to as the "pick-up") is a critical part of the measurement system. Its purpose is to convert the minute movements of the stylus into variations of an electrical signal. The most widely used type of pick-up is the variable inductance transducer (**Figure 51**) in which an armature connected to the stylus arm moves between two coils altering the inductance between them.

The coils are connected in an alternating current bridge circuit (**Figure 52**) such that when the armature is central between the coils the bridge is balanced and gives no output. Movement of the armature unbalances the bridge, which then gives an output proportional to the movement, the relative phase of the signal depending on the direction of movement. The signal from the gauge is processed and sampled within the instrument electronics. The sampled data is then passed to the computer for further processing and appropriate analysis.

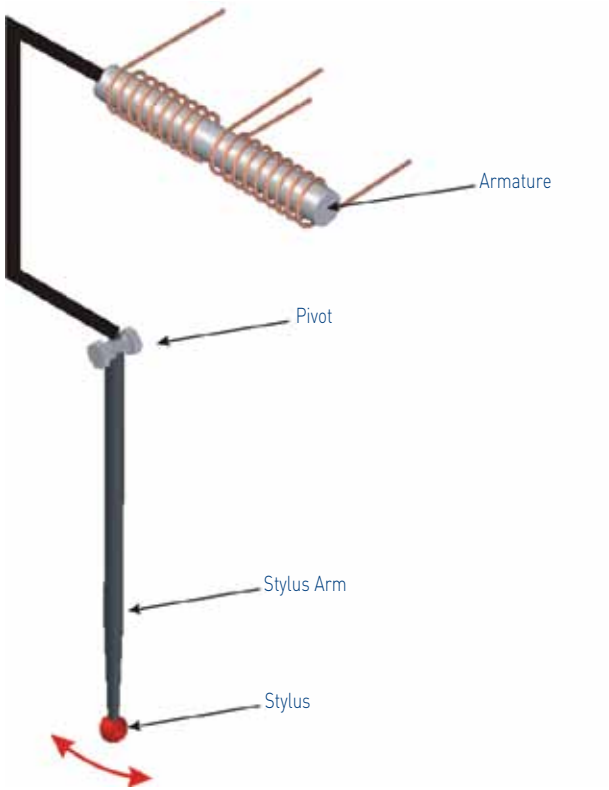


Figure 51: Principle of variable inductance pick-up

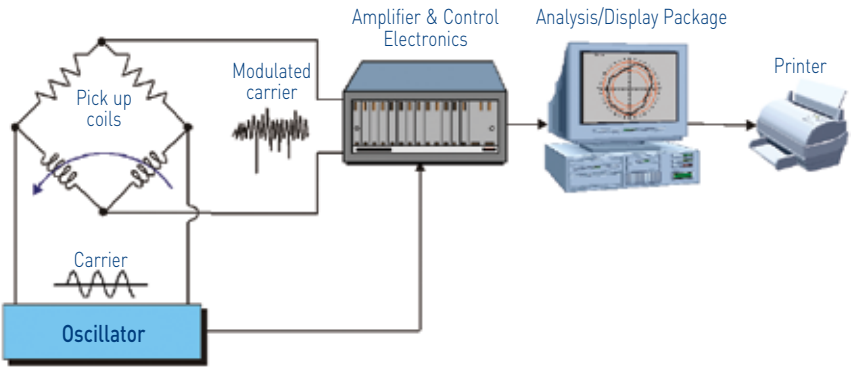


Figure 52: Schematic of typical gauging system

Gauge nomenclature

Modern gauging systems such as the Taylor Hobson Talymin 5 gauge (**Figure 53**) not only combine high resolution with wide range gauging capability, but also provide the operator with an easy method of stylus exchange. Variable angles of contact can be set using a moveable "crutch" mechanism, which is an integral part of the gauge. The Talymin 5 gauge also provides a thumbwheel for adjusting the stylus force and a means for adjusting stylus stop limits.

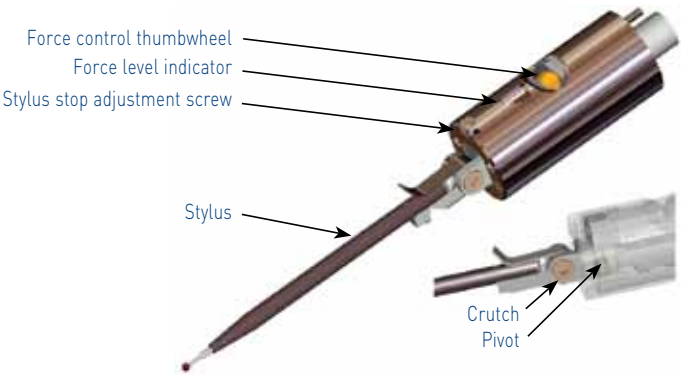


Figure 53: Talymin 5 Inductive Gauge

Gauge sensitivity

The sensitivity required of the gauge used on roundness measuring instruments is indicated by the fact that the stylus arm might be about 100mm long and has to respond to a stylus movement of 0.001µm; the movement of the armature is thus very small and the output from the bridge circuit has to undergo considerable amplification to give an output of sufficient amplitude for conversion to digital data.

Measuring force adjustment

There is an adjustment on the pick-up by which the force with which the stylus bears on the surface can be varied. This is necessary to allow the gauging system to be adapted to the type of measurement being made. For example on a small high precision component a light force might be required so as not to damage the component, but a heavier force might be required on a large, rough textured component in order to ensure that the stylus maintains a good contact with the surface.

Stylus

The stylus is the only contact between the part and the gauge. It is therefore a very important component of the system and its shape has an influence on the information that the pick-up obtains from the surface. Many parts come off a machine with tool marks around the circumference, which are not part of surface geometry (shape) but of surface texture.

A sharp stylus would sink into every scratch and tool mark, and a display of the resulting irregularities could mask the more widely spaced undulations and lobes that contribute to roundness. Consequently, it is normal to use a fairly large ball-tipped stylus which bridges the closely spaced surface texture marks, making the pick-up insensitive to these features.

Selection of the ball tip diameter, typically 1mm, 2mm or 4mm, is dependent on the diameter and surface of the component. Ball tip material can be tungsten carbide, sapphire or other substances with good wear characteristics. The ball tips are usually mounted on a carbon fiber or aluminium shaft.

Special styli can be made for measuring parts or features that cannot be measured using standard styli. Examples of such features include very small diameters, recesses (both internal and external) and deep internal bores.

Gauge orientation mechanism

All roundness measurement systems have some form of gauge attitude and orientation mechanism. These mechanisms allow the user to measure roundness, flatness and straightness on surfaces that are either external or internal as well as upper and lower planes.

There are many types of gauge orientation mechanism. **Figure 54** shows the automatic mechanism patented by Taylor Hobson. One key feature of this mechanism is that the stylus tip rotates about a fixed point as the gauge is moved from vertical to horizontal attitude. This type of mechanism is extremely versatile enabling access to multiple features without user intervention, which in turn allows fully automated measurement programs to be written.

Figure 54: Talyrond 385 automatic gauge attitude and orientation mechanism

Rotational axis (spindle)

The spindle is the single most important component in a roundness instrument. Accuracy of rotation is the key feature since it is the datum from which all measurements are made. However, other features such as stiffness (to cater for eccentric loads), weight bearing capability, "smoothness" (i.e. the amount of mechanical noise that the table injects into the system) and encoder capability are all relevant.

Accuracy of rotation

The axis of rotation must deviate as little as possible from its fixed position in space as the spindle rotates. This means that not only must the bearings be good but, in particular, that they should be as near perfectly round as possible. There are several types of bearings that are used in roundness spindles, each of which have particular strengths and weaknesses.

These include:

(i) Ball bearings

(ii) Oil hydrodynamic bearings

(iii) Hydrostatic bearings

Ball bearing

These three types have different properties and are typically found in different applications. Ball bearings provide useful low-cost spindles and might typically be used in low to moderate load carrying capacity applications. Whilst the general performance is good, one major concern with ball bearing systems is that of "rumble" caused by cyclic errors in the bearing assembly.

Oil hydrodynamic bearing

Oil hydrodynamic bearings are only useful in low-load applications as the spindle needs to be driven up to speed before the lubrication achieves its required thickness to provide the required performance. This type of spindle bearing is typically used in rotating gauge type instruments where the gauge is rotated about the component (see page 61 - "Types of Instruments"). This is because the spindle load is relatively constant. This type of spindle forms the basis of some of the most accurate roundness systems in the world.

Hydrostatic bearing

Hydrostatic bearings fall into two different types: air bearings and oil bearings. The principle is that the lubricating fluid is forced into the bearing under pressure. A lubricating layer is maintained between the surfaces of the bearing components. The averaging effect of the lubricant tends to give these bearings an excellent apparent roundness error. These bearings also tend to exhibit extremely good load bearing capabilities with low coning error (see the section below on page 60) and low noise.

(i) Air hydrostatic bearings are used in low to medium load capacity applications.

(ii) Oil hydrostatic bearings are the preferred solution for high capacity applications.

Apparent roundness error

When discussing the accuracy of rotation there are two figures to be considered: apparent roundness and coning error. The apparent roundness is the most immediately recognizable issue. If a perfect component is measured on a roundness instrument it will appear to be "out-of-round". This is due to rotational errors in the spindle.

Clearly every roundness measurement will have these errors superimposed upon it. These errors will appear as both systematic and "random" errors. Where the spindle exhibits a highly stable apparent form error, it is possible to use error correction techniques to compensate for the systematic errors in order to improve the accuracy of the roundness measurement.

Coning error

The second figure that is of importance when discussing the accuracy of rotation is how the rotational error increases with distance from the spindle (**Figure 55**). This is known as "coning error" – a term indicative of axis precession (think of the wobble of a spinning top) whereby a cone is described about a theoretical perfect axis. This figure should be as small as possible if the roundness error is not to degrade significantly along the length (height) of the component being measured.

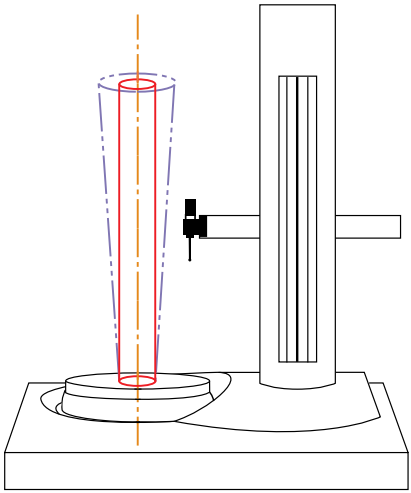


Figure 55: Illustration of coning error

Spindle encoder

The spindle encoder provides positional information and a feedback mechanism that can be used by the spindle control electronics. There are a number of varieties that are used and two different arrangements: in-line or remote. The actual arrangement is of little interest to the user, although there are a number of technical benefits to using a high-precision in-line grating. One important feature that is of interest is the number of counts per revolution that the encoder gives.

This will determine the number of actual locations (data points) logged as the spindle rotates. For a 500upr roundness measurement a minimum of 3600 points are required. However for situations where higher bandwidth filters are used a larger number of points are required. For example if the user is interested in 5000upr, then 36000 points are required per revolution.

Centering and Levelling

A centering and levelling table is necessary to bring the axis of the component into line with the spindle axis. As the centering and levelling table will support the weight of the component, it must be stable under the rated load conditions. There are two basic types of centering and levelling table. The key difference is the way in which the levelling is accomplished.

Spherical seat

The first type of levelling mechanism uses a spherical seat arrangement. Typically the table is controlled by micrometer screws, which push against surfaces on the underside of the table. As the micrometers are adjusted the table will pivot in the seat causing the angular displacement needed to level the component. Two orthogonal micrometers are used.

This type of arrangement readily suits a manual system with a small load capacity. Levelling is carried out in a similar way to centering and is very easy. The table effectively rotates about a point that is above the tabletop. The height of this point is commonly referred to as the **neutral plane**. If the component is centered at this height, then moving the levelling screws will rotate the axis about this point. Levelling can therefore be effected by moving to a different height and using the levelling screws to bring the axis back on center.

For the user there are three main issues with a centering and levelling stage of this type:

(i) Limited overall load capacity

(ii) Limited offset load capacity (typically an offset load must also be positioned along a "load-line" in order to prevent the turning moment of the load from pulling against the springs).

(iii) If the component cannot be centered at the neutral plane (perhaps because of fixturing) manual centering and levelling becomes difficult.

Kinematic three-point levelling

The second type of levelling mechanism uses a kinematic three-point levelling system. As a manual arrangement this would be much harder to use than the spherical seat arrangement. However, when coupled with a computer control system and fully automated, this arrangement overcomes all of the above issues.

Taylor Hobson introduced this patented approach in the 1980's on the Talyrond 300 instrument, which was the first in a well-established line of fully automated roundness systems using this principle.

Linear axes

The other major axes of a typical automated roundness instrument capable of measuring all aspects of cylindrical form are the "radial straightness" and "vertical straightness" units. There are a number of issues that affect the overall performance of the instrument, and these are discussed briefly below.

Straightness

It almost goes without saying that the axes need to be straight! A good straightness axis will be better than 1µm along the measuring length. If the apparent form errors are repeatable, this will allow datum correction to be applied in software to reduce the overall measurement uncertainty.

Alignment

The alignment of the axes is crucial. The column must be aligned to be accurately parallel to the spindle axis in both the measuring direction and the orthogonal direction. The radial straightness unit should be aligned to be square to the column.

Accuracy of movement

When moving the column carriage or the radial straightness unit it is essential that the movement is parallel or square to the spindle axis as appropriate. For example the carriage must not tilt as the arm is moved, as this would affect any multiplane flatness measurement or radial straightness measurement.

Positional accuracy

One key factor in assessing the uncertainty of a measurement solution is the repeatability of the results on the type of component to be measured. For most components the form error on the component will contribute significantly to the overall uncertainty. If a component with form error is measured repeatedly, any positional errors in the axes will be translated into changes in the measured values. This will affect the overall repeatability result. In order to overcome this, positional uncertainty of the axes must be kept to a minimum.

Electronics

Instrument electronic systems cover two aspects: control and data acquisition. The electronic control system is responsible for controlling movements and speeds and so is directly responsible for positional accuracy (see above). Control is usually achieved by means of DC servo systems using encoders or gratings to provide the feedback elements.

The electronic data acquisition system is responsible for collecting the data from the gauge and preparing it for analysis. Usually the gauge (and axes) positions are sampled at points determined by the encoders or gratings being used. These samples may need pre-processing by the electronics (for example pre-filtering) prior to presenting the data to the analysis software. The design of the data acquisition electronics is extremely important. Any noise introduced at this stage will degrade the overall performance of the measuring system.

Software

Modern digital systems make use of personal computers of one form or another. The computer provides a human-machine interface, accepting input from an operator while providing results, displays, printouts, data storage, etc. Each different instrument manufacturer will have a different approach to providing these facilities, so comparison of the software is mostly subjective. One key area however is the algorithms that are used to provide the data preparation, filtering and parameter calculation. The requirements for these aspects are controlled by ISO standards and so a high degree of conformity is required in this area.

Programmability

Some modern instruments support the creation and use of measurement programs. The typical programming approach is to use a "first of type" part with the instrument in "learn mode". In this mode each instrument positioning move, measurement step and analysis routine is "learned" and a program thus created. The program can then be re-run on parts of the same type thus saving time, reducing operator intervention and improving measurement repeatability and accuracy. Programs can easily be edited for use on similar components, again saving time.

Types of Instrument

Roundness measuring instruments are of two basic types – rotating workpiece and rotating pick-up. So far we have looked at the rotating workpiece type (see **Figure 56**). In this type of instrument the workpiece is rotated against a stationary pick-up. In the other type, rotating pick-up, (**Figure 57**) the workpiece is stationary and the pick-up revolves about it. Each type has its advantages and is more suitable for certain types of measurement; the choice must depend largely on the measurements to be made and the size and shape of the parts the instrument is intended to measure.

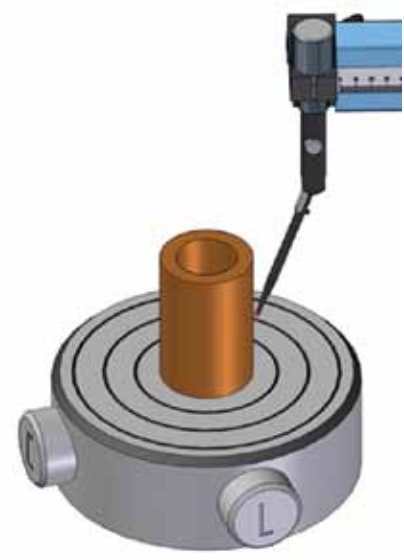


Figure 56: Turntable type instrument

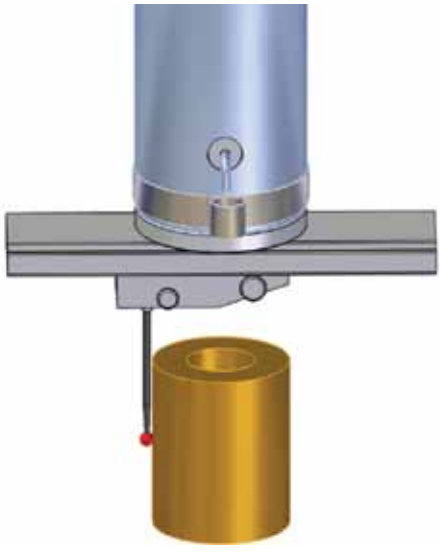


Figure 57: Rotating pickup type instrument

Rotating workpiece type

This type of instrument (**Figure 56**) is mostly applicable to general roundness applications and the measurement of parts that have a cylindrical operating envelope, e.g. sleeves, bushings, shafts crankshafts, etc.

Since the pick-up is not associated with the spindle, this type of instrument is readily adapted to measurements associated with cylindrical form, including flatness and straightness.

The weight of the turntable and the workpiece being measured has to be supported by the spindle bearings, and this places a restriction on the weight of parts that can be measured. Any load whose center of gravity is offset from the spindle axis will exert a turning moment about this axis. This turning moment must be maintained within certain limits for the spindle to continue to function accurately.

Rotating pick-up type

This type of instrument (**Figure 57**) is mostly applicable to specialist applications and to high load components that do not have a cylindrical operating envelope, e.g. engine blocks, cylinder heads, large connecting rods and other similar components.

The worktable, not being part of the measuring system, can be of substantial construction, so the weight of the workpiece is not a limitation of measuring capacity. Many large parts (e.g. cylinder blocks) are of unsymmetrical shape, with the center of the bore or surface to be measured offset from the center of gravity; this offset load is not a limitation with this type of instrument. Long shafts and crankshafts can also be accommodated.

Because the precision spindle only has to carry the comparatively light (and constant) load of the pick-up, the accuracy is not affected by the component weight. The most accurate roundness instruments in the world therefore tend to be based on this principle.

One disadvantage of the type of instrument is that the distance from the end of the spindle to the tip of the stylus limits access to the component. To adapt the instrument to measure deeper components requires the use of a spacer (or "drop-arm") between the spindle and the gauge body. This increases the measurement loop and therefore increases the sensitivity to external influences such as vibrations that may degrade performance of the instrument. If a wide variety of sizes are to be accommodated, then a large number of drop-arms may be required.

Figure 58 and **Figure 59** show a rotating pick-up instrument measuring engine components. In **Figure 59** the requirement for a long drop arm to access the distal end of a camshaft bore is clearly seen.

Figure 59: Use of a drop-arm enables the measurement of a camshaft journal within a cylinder head

Figure 58: Talyrond 450 is an example of a rotating pick-up type roundness instrument

Chapter 7- How to get the best out of your roundness instrument

As with any precision instrument, the correct environment, set-up, calibration and measurement method are necessary to get the optimum performance out of a given instrument. This chapter looks at these issues. Clearly, the quality of the instrument itself will dictate the limit of the accuracy that can be achieved, even with the best method. Where relevant, key specification criteria for instruments are also covered.

Environment

Roundness, cylindricity and form measuring equipment is expected to measure features with amplitudes often less than a micron and with sub-micron accuracy. The installation site of the instrument is a key factor in being able to achieve such precision, as the instrument will be sensitive to environmental influences such as temperature variations and vibrations.

Manufacturers go to great lengths to design the instrument to be as tolerant to environmental conditions as possible and, in some cases, excellent "immunity" can be obtained from certain environmental factors – but not all.

It is good practice – regardless of the instrument's design – to install it in a location that will minimize the impact of environmental factors as sources of error in the measurement.

Vibration

Vibration is perhaps the most obvious environmental factor to consider: it is not difficult to appreciate that it can have a direct influence on the measurement results. Vibration can reach an instrument either by direct transmission (e.g. floor-borne vibration) or via the surrounding air (air-borne). As a guide the following factors should be considered.

Possible sources of floor-borne vibration:

(i) Large machinery located nearby (hydraulic presses, compressors, etc.)

(ii) Nearby roadways or railways or vehicle traffic in the plant

(iii) Other machine tools mounted on the same foundations

(iv) Insecure foundations (e.g. as on 2nd floor or greater)

Many instruments will include some form of isolation system. These can range from simple cushioning pads to air filled bladders that reduce the effects of floor-borne vibration.

Direct sources of vibration:

(i) Any part of the instrument being secured or in contact with the room structure other than the floor, either directly or indirectly. As an example, a bench pushed up against the instrument could transmit vibration from the floor directly into the instrument, by-passing any anti-vibration systems.

(ii) Operator influence such as using the frame as a footrest, or the instrument surround as a table, during measurement.

Air Borne Vibration/Instability:

(i) Ceiling and/or air conditioning fans

(ii) Door closing mechanisms

(iii) Draughts from windows/doors/air conditioning equipment

(iv) Loudspeaker systems

Temperature

The next most significant environmental factor that should be considered is temperature. Roundness measurement, and especially multi-plane cylindricity or flatness measurements, can take several minutes. During this time it is essential that the temperature remains constant. In fact, controlling rate of change of temperature is more critical than what the actual temperature is.

Typical causes of temperature instability include:

(i) Draughts from doors or windows can create temperature gradients

(ii) Solar heating can cause differential heating on an instrument if installed near a window

(iii) Installation below or near air conditioning ducts and radiators

A good metrology laboratory will control all of these variables. The floor may be mechanically isolated from the rest of the site (for instance by shock absorbers) to limit floor borne vibration. A temperature control system might be used to maintain a fixed temperature (usually 20ºC) to better than ±1ºC and in high quality environments to ±0.1ºC.

Inspection in production environments

In manufacturing, measurements are often needed near-line or on-line in the production environment. If high quality measurements are needed a "local environment" can be created to approximate as much as possible the ideal environment of a metrology laboratory.

An example of this principle is shown below in **Figure 60**. This instrument, a Talyrond 595, incorporates active anti-vibration mounts to provide isolation against floor-borne vibration and an environmental cabinet to guard against air-borne vibration and to limit the effect of temperature changes.

Figure 60: Talyrond 595 high precision roundness system incorporating active anti-vibration mounts and an environmental enclosure

Calibration

Calibration is an essential part of any measurement process and is simply the removal of repeatable errors in the instrument. Without a known level of confidence in the accuracy of the result it would not be possible to achieve interchangeability of parts or possibly even the mating of parts if they were measured on two different systems. Whilst system accuracy is the objective, in practice the different aspects of the instrument must be calibrated separately. The following sections deal with the gauge, the rotary datum, and the straightness datums.

Gauge

The primary measuring component of any inspection system is the gauge which may utilize interchangeable arms of different lengths with a variety of stylus tip shapes and sizes mounted on them. It may also have a moveable crutch to change the angle at which the stylus arm is positioned. These items will affect overall gauging characteristics including gain and linearity.

Normally linearity error is very small, typically of the order of 1%. Because measurements record departure from true form, the gauge deflection is also very small and so the linearity error can generally be ignored. Linearity calibration is therefore not usually performed.

The gain of the gauging system will be affected by variations in gauge arm length, stylus tip geometry and crutch angle. Gain error may be several percent and will directly influence the measurements. The gain must therefore be calibrated, typically by measuring a known deflection. There are two ways in which this is normally achieved on a roundness instrument, the first being to use a "flick"standard (**Figure 61**) and the second being to use gauge blocks (**Figure 62**). These two calibration standards are shown below.

Figure 61: Flick Calibration Standard

Figure 62: Gauge Block Calibration Standard

Flick method

The "flick" method of measurement is perhaps the most convenient method since it is done in the same manner as making a roundness measurement. Once centered and levelled to the instrument spindle, the flick is measured between the indicated lines using the chosen stylus configuration and at the desired crutch angle (**Figure 63**).

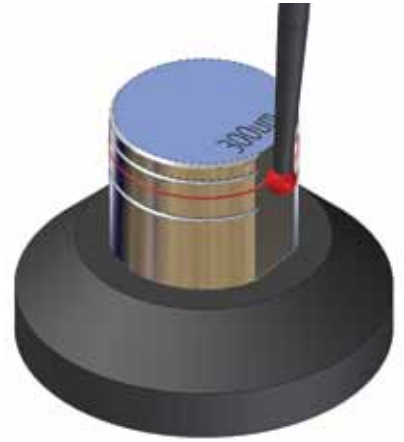


Figure 63: Measurement of Flick Standard

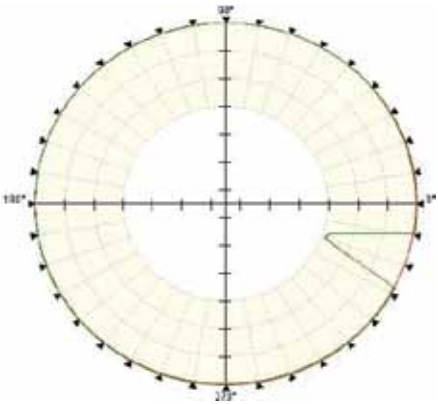


Figure 64: Analyzed Result showing 'depth' of flick

The depth of the flick marked on the standard is then compared with the measured roundness value (typically using a Minimum Circumscribed Circle, **Figure 64**). The gain correction factor is then given by:

$$\text{Gain Correction Factor} = \frac{\text{Actual Difference}}{\text{Measured Difference}}$$

Most modern instruments will have a measurement and analysis routine that will perform this calculation and make the gain correction factor adjustment automatically, with the added advantage that they employ a process that more closely replicates the method by which the standard is calibrated.

Gauge block method

The gauge block method (**Figure 62**) is very similar in principle to the flick method. However, it does require a greater level of manual intervention, especially in terms of setting-up and movement of the stylus across the surface of each gauge block.

The gauge blocks are wrung down side-by-side on an optical flat. The optical flat is then accurately levelled on the instrument worktable. The stylus is brought into contact with the gauge blocks such that rotation of the worktable will cause the stylus to traverse across two adjacent gauge blocks whose difference in thickness is appropriate for the calibration of the particular gauge range (**Figure 65**).

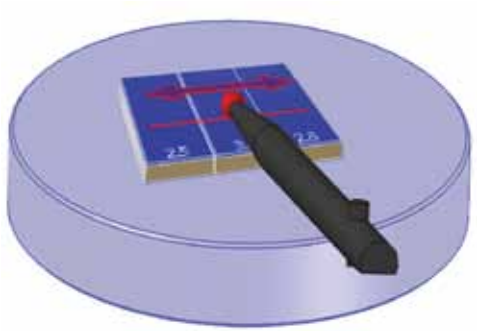


Figure 65: Calibrating the gauge using gauge blocks

The instrument gauge reading is noted at each of the positions with the stylus at the central position of each gauge block. The difference in values is then compared to the differences in marked values on the gauge blocks. As with the flick standard, the gain correction factor is then given by:

$$\text{Gain Correction Factor} = \frac{\text{Actual Difference}}{\text{Measured Difference}}$$

Automatic method

Since the stylus or its crutch angle may be changed on a frequent basis it is often necessary to perform a calibration of the gauge prior to measurement. On an instrument featuring a radial axis with high quality scales, a gauge calibration can be performed simply by moving the radial axis while the gauge is in contact with a stationary surface. This method of calibration is very quick (typically under 15 seconds) and very convenient.

Although it is not directly traceable to National Measurement Standards, this type of automatic calibration is sufficiently accurate for many applications.

Rotational datum

So far in this book it has been assumed that the rotational datum (spindle) that is central to the roundness measurement method is "perfect". In real life this is never the case and even the most carefully manufactured spindles will have imperfections.

The principal imperfection that we are interested in here is the roundness, although other errors such as axial pump (the tendency of the table to rise and fall very slightly as it rotates) and pitch (the tendency of the table surface to tilt very slightly as it rotates) also exist. The roundness errors can be split into two fundamentally different kinds: repeatable and non-repeatable. The repeatable errors can be measured and eliminated using software corrections. The non-repeatable errors cannot be eliminated by software correction and will contribute to the overall measurement uncertainty.

Figure 66: Hemispherical standard

The basic principle of software compensation is to measure a component that has been calibrated for roundness in a suitably accredited calibration laboratory. As the measurement is a combination of spindle errors and component errors, if the component errors are known they can be subtracted from the measurement to identify the spindle errors. The spindle errors can then be stored and subtracted from future roundness measurements leaving just the out-of-roundness errors of the component.

As mentioned above, the spindle will exhibit repeatable and non-repeatable errors. To minimize the influence of the non-repeatable errors in the calibration process it is normal to measure the calibration standard several times and to average the measurements prior to determining the spindle errors.

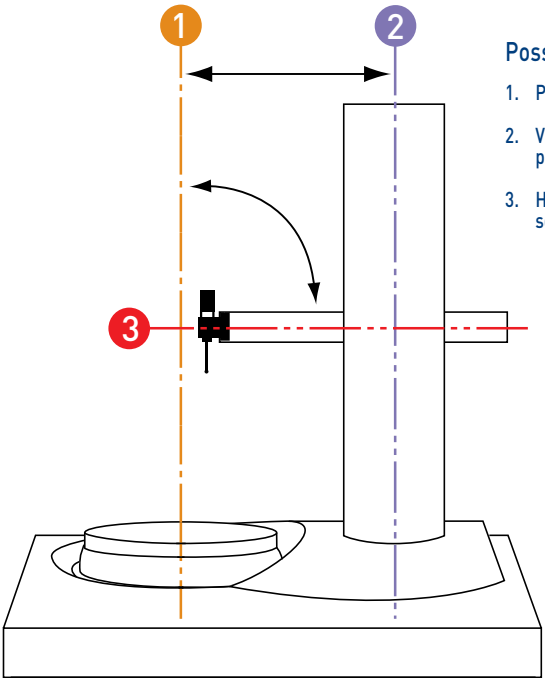
There are other techniques that can be used for calibrating roundness errors. These normally rely on some form of error separation method wherein the hemispherical standard (**Figure 66**) is rotated to more than one position. This type of technique is employed in the calibration laboratories and is beyond the scope of this text.

Linear axis form errors

Straightness, cylindricity and multi-plane flatness will all be affected by errors in the motion of the linear axes. The effective form of these errors introduces an uncertainty into the final measurements. Like the spindle form errors, the form errors of the linear datums again fall into the two categories of repeatable and non-repeatable errors. Once more the repeatable errors can be separated out and corrected for by measuring suitable reference standards. In this case the standards would be a precision cylinder and a precision flat.

Alignment errors

One further area of complexity when considering the overall accuracy of a form-measuring instrument is the parallelism or orthogonality of the axes (**Figure 67**). As an example, it is easy to see that if the column leans away from a perfectly centered and levelled cylindrical component, then the radius of the component will appear smaller at the top than at the bottom. If the component is turned on end and re-measured, the problem will persist. Similar problems will exist for multi-plane flatness if the radial axis is not accurately square to the spindle axis. It is therefore essential to ensure that the axes are mutually orthogonal.



Possible alignment errors

1. Primary datum: roundness error
2. Vertical axis: straightness and parallelism to primary datum
3. Horizontal axis: straightness and squareness to primary datum

Figure 67: Possible sources of alignment errors

Traceability

Manufacturers and suppliers of all types of components and products carry out measurements of a variety of features in order to maintain quality and compatibility of supply.

With the ever-increasing trend to sub-contract components in order to minimize cost and remain competitive, the need for absolute measurement methods and techniques takes on greater importance.

As individual companies often have different metrology equipment and techniques, there is a need to establish a benchmarking system that proves and compares the capability and results across the spectrum.

This is done using calibration or verification standards that are traceable (through a hierarchy of calibrated measurements) to the national standards bureau of individual countries. These agencies also collaborate between themselves to agree and cross check their own master standards to ensure that there is global compatibility and agreement of measurement results.

Calibration of an instrument is said to be traceable when the masters or artifacts used in the calibration process have been certified and given a definitive value by a recognized authority or laboratory further up in the national chain of measurement. As with all calibrations, the value shown on the certificate will be qualified with an "uncertainty" figure. This uncertainty value should be taken into account when calculating the uncertainty in the final measurement results.

To ensure compliance to international standards, all individual masters and calibration standards require periodic re-certification on a frequency dictated by their importance, accuracy and use.

Set-Up

Consideration should always be given to setting-up or staging of the component in preparation for taking the measurement in order to achieve consistent and correct results.

Fixturing

Fixturing (or "workholding") during both manufacture and measurement can play an important part in the results obtained. Consider a round bar or ring-type workpiece held firmly in a 3-jaw or 5-jaw chuck for grinding or turning. The component is compressed at the points of contact (see **Figure 68**), giving rise to stresses in the material.

Even if the workpiece is turned or ground perfectly circular on the machine, when it is removed from the chuck the stress in the material will be released, giving rise to three or five lobes. The same condition may exist during measurement if the workpiece is held too firmly in the jaws of the chuck.

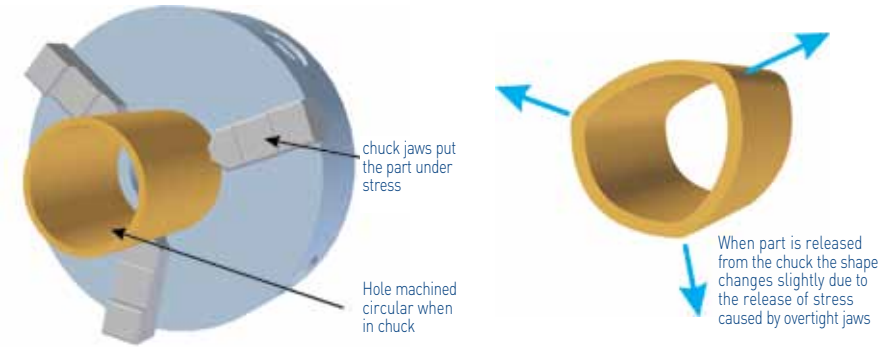


Figure 68: Method of workpiece holding can effect roundness

Centering and Levelling

Because the workpiece has to be positioned on the axis of rotation of the instrument, centering and levelling adjustments are necessary; procedures and techniques for doing this are described in detail on page 60. Many factors affect the required degree of centering and levelling that is required when measuring a component. These factors include the quality and size of the component.

Ideally the component should be centered and levelled to the point at which additional centering and levelling has no influence on the measurement result. Many modern instruments are capable of quickly and automatically centering and levelling the component to optimum levels without operator intervention.

Cresting

Another consideration when using a roundness instrument is that of cresting. This is the alignment of the stylus and gauge such that the measurement plane of the gauge passes through the center of rotation. If the component is not centered and levelled accurately, then the cresting error will increase the uncertainty in the measured roundness value.

Cresting errors give rise to a distortion in the measured form and the position of the center of a roundness measurement. If the cresting is not properly set, then the error in the calculated eccentricity can affect the time taken to center and level the component.

Methodology

The other considerations in the measurement of roundness and form relate to the approach that should be taken. Good metrology practice will provide dividends in improved repeatability and reproducibility of results. There are many factors to consider, some of the more important ones are listed below.

(i) **Handling of component** Try to minimize the handling of the component. Handling tends to warm the component, setting up temperature gradients that may affect the measurement. The component should be cleaned before measurement and ideally allowed to come back to thermal equilibrium prior to starting the measurement.

(ii) **Know what you are measuring** It is important to know the bandwidth of the data that must be represented. Consideration of the surface wavelengths or harmonics of interest will help in the selection of appropriate styli and measurement speeds. The workpiece material might also influence the stylus tip material chosen.

(iii) **Understand the required accuracy** It is important to have an appreciation of the uncertainties of measurement prior to using the instrument. For example high-accuracy measurement of roundness less than 1μm requires the component to be centered to better than 1μm. Measurement of surfaces with a larger RONt might allow the centering requirement to be relaxed.

With suitable training and experience the user should be able to develop sound measurement practices for assessing most components. Variability in results can be reduced if such processes are followed.

Chapter 8 - Advanced applications

Interrupted surfaces

There are many components that are required to be round that have interrupted areas, for example a fluid dynamic bearing, a commutator on a motor armature or a crankshaft bearing with an oil hole.

These types of surface are not difficult to measure, however, they do require a little more thought both when measuring and when analyzing.

Figure 69a: Example of interrupted surface

Stop attachments

The first requirement for measurement of interrupted parts is to prevent the stylus bouncing or catching at the point of each trailing and leading edge of the interruption. Reducing the measurement speed may help but is not always practical and seldom eliminates the problem. Increasing the stylus tip radius may help but will also have an undesired mechanical filtering effect, particularly on very small components.

Figure 69b: Typical iris mechanism

A stylus stop attachment, which limits the amount of negative stylus movement, is the best solution for preventing the stylus from bouncing or catching.

There are two common methods of limiting the stylus movement. One type involves the use of an iris type shutter similar to that employed on a camera (**Figure 69b**); closing of the iris prevents the stylus from excessive movement. The part and the tip diameter of the stylus usually dictate the amount of limitation required. A second option is to use an adjustable end-stop, as shown in **Figure 70**. Both of these methods enable the operator to make the necessary adjustments to cater for the measurement of interrupted features.

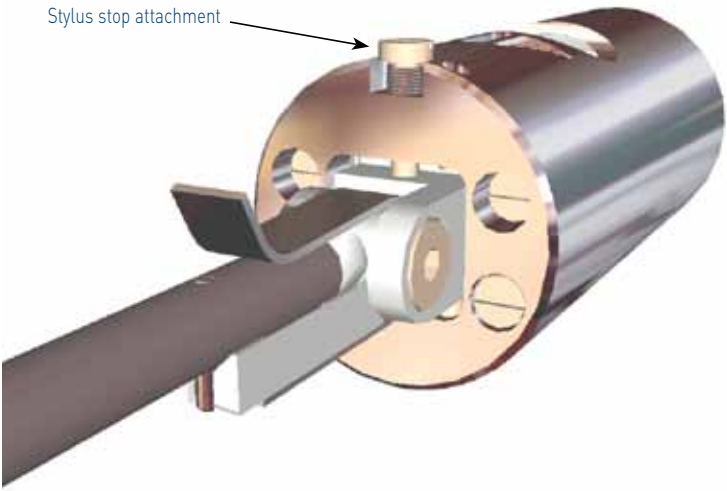


Figure 70: Integrated stylus stop attachment

Hole removal

However the interrupted surface is measured, data will have to be removed from the regions surrounding the interruptions in order to analyze the roundness of the component. This data can be removed in a number of ways.

Manual data removal

The first and most simple method is to provide a means for the user to identify the regions manually. Often this is done using cursors. These cursors can also be programmed to allow deletion of data at set angular positions. There are limitations to these techniques. With the manual selection method the operator has to make a judgement as to where data should or should not be excluded, which may cause repeatability problems. When the programmed position method is used the component must be placed in exactly the right angular position on the roundness instrument table.

Automated data removal

Another option is to completely automate the data removal process that improves repeatability and simplifies mounting of the component on the instrument table.

A technique often used for automatically removing data relies on the setting of a "gauge under-range" threshold. Data below this threshold is assumed to be due to the interruption, and is automatically marked for deletion. This can be coupled with the ability to remove a pre-defined amount of data adjacent to this automatically marked region. This allows the user to account for area where the stylus drops into the interruption.

There are other techniques or refinements to the foregoing technique that can be used for automatic data removal, however detailed description of these techniques is beyond the scope of this book.

Cylindrical mapping

A new measurement technique incorporated in a number of roundness instruments is that of cylindrical mapping. Cylindrical Mapping is a term used for the measurement of 3D surface topography on rotationally symmetric components. A measurement is made by taking a series of axial straightness traces at different spindle positions. Because each trace has an angular, radial and vertical relationship they can all be combined into a single three-dimensional (3D) file.

Previously this type of measurement could only have been made using a surface finish instrument with special fixtures and a rotary stage. A key benefit of using a roundness instrument for this application is that the component can be aligned to its axis (via center and levelling) much more easily and can be measured on the same instrument used to check other rotational features.

Figure 71: Talyrond instrument mapping a crankshaft oil hole

Some examples of how cylindrical mapping may be used are as follows:

(i) **Oil Hole Washout** Analysis of oil holes on bearing surfaces such as crankshaft pins and main bearings

(ii) **Rotational steps** Detailed analysis of rotationally stepped items such as commutators or brushes

(iii) **Twist or shaft lead** Detection of spiralled grooves that cause leakage on bearing seals

(iv) **Wear Scars** Testing of engine components after running-in for manufacturers or producers of oil and oil additives

(v) **Grooves** Geometrical analysis of machined grooves critical to bearing function (e.g. for hydrodynamic bearings)

(vi) **Machining Defects** Detection of burrs, scratches and other unwanted machining errors

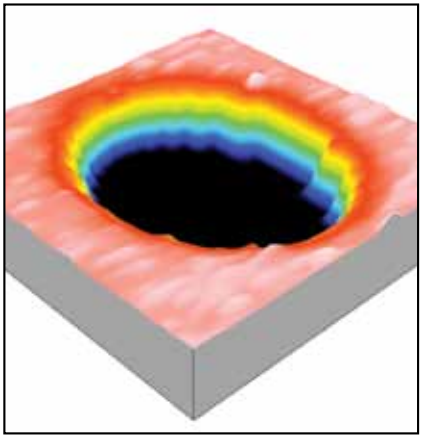


Figure 72a: Example of correct oil hole

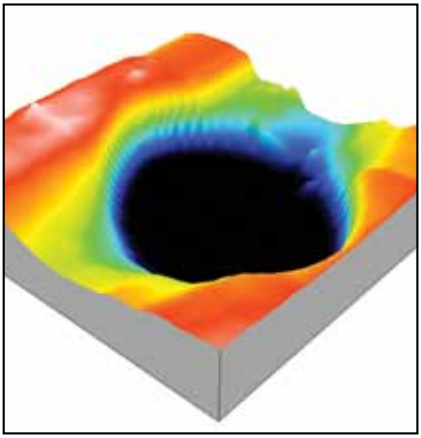
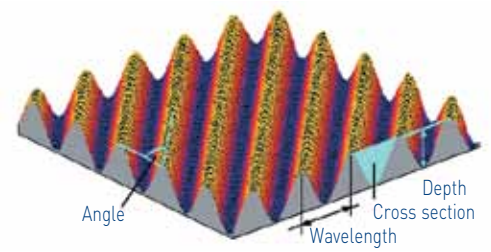


Figure 72b: Example of oil hole with washout



Test Sample 05		
Wavelength	=	0.100 mm
Depth	=	1.565 μm
Gradient	=	3.000 mm
Cross section	=	78.000 μm^2
Starts / rev	=	30 left
Angle	=	0° 41'
Diameter	=	80 mm

Figure 73: Twist Analysis Results

Twist analysis

A large number of applications incorporate a lubricated shaft running through a lipped polymer seal. Adverse lay on the shaft can cause leakage (due to pumping action) or dry running, which will lead to premature failure of the seal. Traditional methods for assessing the lay of the shaft involve hanging a weighted thread over the shaft. The shaft is then rotated and the movement of the thread is noted. This gives a rough guide to the lay on the surface.

A better representation can be achieved by using the cylindrical mapping method described above and then applying "Twist" analysis (sometimes referred to as "Lead" analysis), a technique recently developed and patented by Daimler-Chrysler AG in Germany. This new method of quantifying the lay on a ground shaft involves analyzing the frequency content of an areal map of the surface. A special filter is used to isolate the important lay. Parameters are then calculated based upon the amplitudes of the most significant frequencies found in the filtered surface.

The lay effectively consists of a number of helices around the surface. The twist parameters include the wavelength of the principal lay component (measured in the axial direction), the peak-to-valley depth of this component, the number (starts/rev), angle and pitch of the helices. A theoretical cross-section parameter is also given in order to help quantify the pumping action of the lay.

Wear scar analysis

The accurate assessment of the amount of material worn away during running is important in lifetime performance studies. There are many factors that cause unnecessary wear resulting in breakdown or failure. There may not be enough valleys in the surface to allow oil retention or there could be too many peaks resulting in excessive material contact.

Oil producers play a part as well by identifying whether they are getting the correct lubrication qualities from their oils and examining the effects of performance enhancing additives.

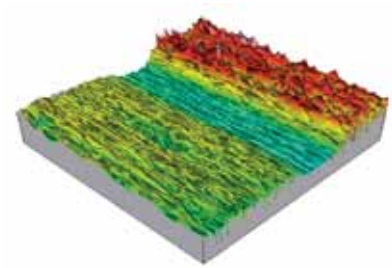


Figure 74: Wear Scar from a rocker arm

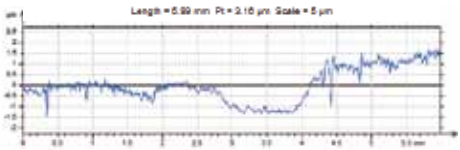


Figure 75: Extracted profile

Measuring wear on internal bores is a universal problem, particularly if a full 360° of rotation is required. **Figure 74** shows the 3D image of a wear scar found on the internal bore of a rocker arm. It is also possible to extract the individual traces through the measured area (see **Figure 75**). In this case the worn, partially worn and unworn parts of the surface can be seen quite clearly.

Groove analysis

At the heart of every modern Hard Disk Drive (HDD) is a bearing that allows the platens to rotate at speed under read/write heads. Historically, high precision ball bearings were used; however, modern HDD's tend to incorporate Fluid Dynamic Bearings (FDB) due to their improved speed and Non-Repeatable Runout characteristics.

In fluid dynamic bearings, the bearing function is taken over by a layer of lubricant less than one tenth the thickness of a human hair. The rotor supported by the bearing essentially floats around the shaft. The elimination of metal-to-metal contact in fluid dynamic bearings eliminates non-repeatable runout due to surface imperfections. In a hard disk drive application this makes it possible to reduce track spacing and increase the track density on the disk.

Figure 76: Hard Disk Drive Bearing assembly

The rotational function of an FDB is enabled through a spiral groove pattern that is machined onto the rotor and hub of the bearing. This groove pattern allows the lubricant to flow in a defined manner, which generates a fluid film layer between the rotor and hub when the bearing is rotating at speed. Of critical importance to the fluid film layer are the structure, shape and spacing of the grooves on the rotor and hub.

Special analysis software is used to enable FDB manufacturers to monitor the shape and pitch of grooves on their rotors and hubs. A typical analysis is shown in **Figure 77**. This provides information on a wide range of parameters including:

(i) Roundness, eccentricity and eccentricity position

(ii) Groove depth (Max, Min and Average)

(iii) Groove width (Max, Min and Average)

(iv) Groove pitch ratio (Max, Min and Average)

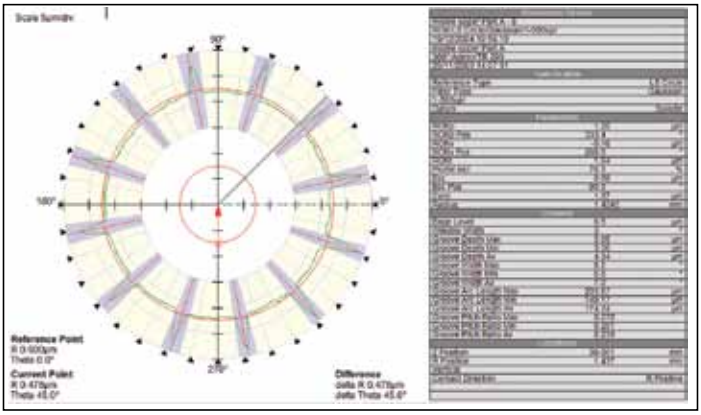


Figure 77: Groove analysis of Fluid Dynamic Bearing through Ultra software

Piston Analysis

Pistons are designed to accommodate distortion caused by heat and other stresses during operation. The resultant unique shapes are difficult to define using normal geometrical analysis such as cylindricity, roundness and straightness. Special software, such as that offered by Taylor Hobson, allows piston design data to be compared to piston measurement data. Results will show any deviation from the desired shape as well as the information required to make adjustments to the manufacturing process.

The measurement of a piston requires analysis of both roundness and straightness profiles. Information is usually supplied as a table of "drops" from a given circle or line. Other parameters such as the relationship between the gudgeon pin bore and the axis of the piston can also be calculated.

Commutator - rib step analysis

In an electric motor a major factor contributing to commutator brush wear is the differing step heights of the individual commutator ribs. Ideally the ribbed portion of the commutator should have a smooth transition between adjacent steps. Where this is not the case, it can cause excessive sparking of the carbon brushes, which in turn creates electrical interference, heat and, in extreme cases, motor fire.

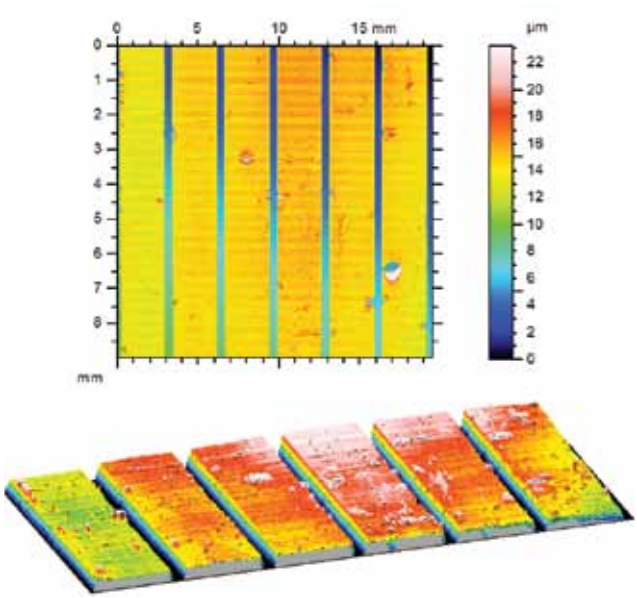


Figure 78: Commutator rib step analysis example

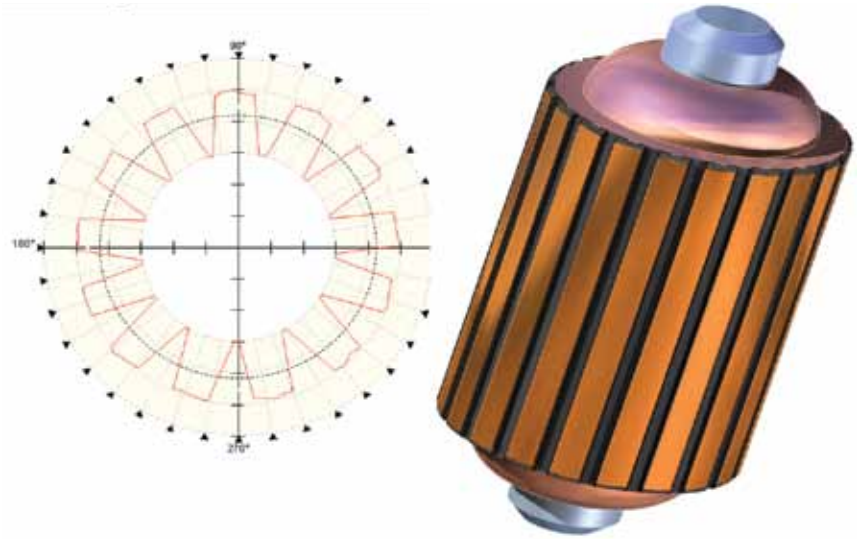


Figure 79: Commutator and typical roundness measurement

Traditional methods of analysis have involved taking a roundness measurement (**Figure 79**) of the commutator at various points in order to assess both the cylindricity and roundness of the commutator. While this type of measurement gives a good indication of whether the ribbed steps of the commutator are correct in terms of geometry it does not enable the user to quantify errors such as the step between two adjacent ribs (see **Figure 78**).

Special software can be used to analyse the step errors between adjacent ribs. This software can provide results such as:

(i) The Maximum step height between ribs or the maximum step height between highest peaks

(ii) The Average step height

(iii) All step height values

(iv) The roundness value of the whole profile (excluding gap regions)

(v) The eccentricity

(vi) The runout value to the spindle

Velocity analysis

As previously discussed, harmonic analysis is a useful tool for manufacturers to use in gaining a better understanding of issues associated with their process. However, it is less useful in predicting performance of the component when in use.

Velocity analysis combines harmonic analysis with rotational frequency to provide a better understanding of how a component will function in a particular assembly. The rotational frequency is a variable set by the user and it is dependent on the particular component under analysis.

The analysis provides the ability to look at velocity parameters within defined bands of harmonics. The velocity parameter for each harmonic within a band is calculated using the following equation:

$$V_{(\mu m\ /\ sec)} = 2\pi F A N$$

Where: **V = Velocity at a particular upr** **F = Frequency (input by user)**
A = Amplitude of harmonic **N = Harmonic number**

The output for the analysis on a component is shown in **Figure 79**. The results incorporate a polar plot with associated roundness results, velocity parameter calculations within bands, tolerance information and a velocity spectrum.

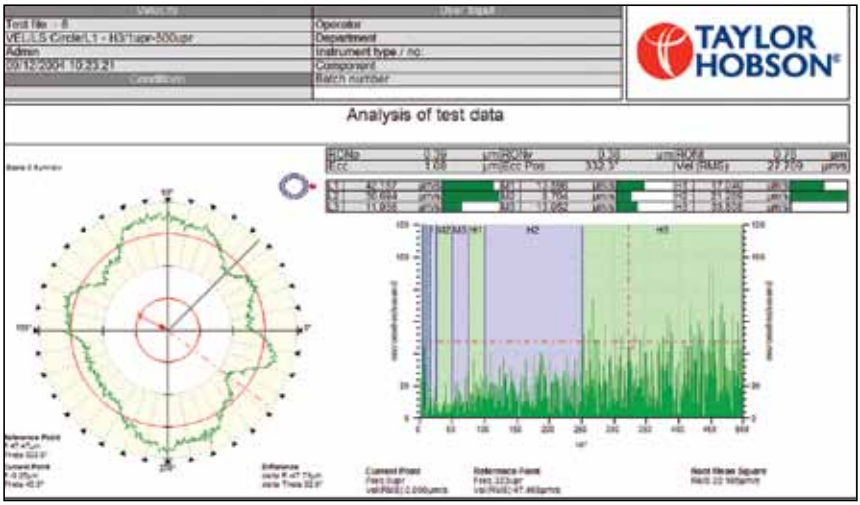


Figure 80: Velocity analysis output

Radial and Axial Wall Thickness Variation (WTV)

Radial WTV measurements are completed by obtaining polar traces of both the inside and outside of a component at the same vertical height (Z position). **Figure 81** shows analysis results on a bearing race. Axial WTV measurements are completed by obtaining upper and lower pairs of flatness traces in the same radial positions on a disc. **Figure 82** shows the measurement set-up for a brake disc.

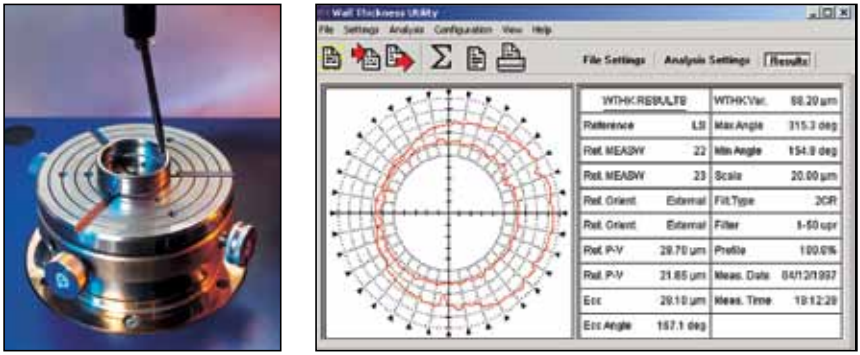


Figure 81: Measuring Wall Thickness Variation on a bearing race

Figure 82: Measuring Wall Thickness Variation on a brake disc

Surface Texture

As the tolerances of form (e.g. straightness) become ever tighter, their measurement is influenced by the surface texture of the component. The surface texture also affects the overall performance of the component, and usually has to be measured separately from the form. This often involves the use of dedicated surface finish measuring equipment.

One of the most recent developments in roundness measurement instrumentation is the addition of a surface finish measurement capability. In many applications the use of a roundness instrument for measuring surface texture has the advantage of reduced setup time, as the component axis will have been aligned during the measurement of roundness. Needless to say, if the measurements can be made on a roundness instrument, then the cost of the surface texture measuring instrument can also be saved.

In order to equip a roundness instrument for measuring surface texture, certain key enhancements are required:

(i) **Stylus and stylus force** A diamond stylus (typically with 10μm tip radius) and low force is required instead of the ball tip probe used for roundness.

(ii) **Data density** Surface analysis requires more closely spaced data than form analysis

(iii) **Low noise** The movement of the measurement axes must generate very little noise so as to prevent swamping or obscuring the roughness data

The assessment of surface texture is beyond the scope of this book. For more information the reader is referred to the companion text: **Exploring Surface Texture**, also published by Taylor Hobson Ltd.

Appendix 1 - ISO Standards

Roundness, cylindricity and form measurement, like many other types of measurement, are the subject of National and International Standards. These specify the way in which measurements should be made and how the results are to be expressed (e.g. which reference circles are preferred). Conformity to these requirements ensures that measurements made on different instruments are compatible which is essential when parts made in one country or by one subcontractor have to be matched with parts made elsewhere.

Manufacturers of measuring equipment usually ensure that their instruments conform closely to the requirements of a Standard, so a designer knows that when he specifies a certain tolerance, that part can be inspected, measured, and either rejected or accepted, to this value unambiguously, not only in his own factory but anywhere in the world.

Many countries adopt the ISO standards as their primary standard. For reference, the appropriate standards as at the time of publication are shown in **Table 2**.

Table 2: ISO Standards relevant to the topic of Roundness & Cylindrical Forms

Standard	Title
ISO 1101:2004	Geometrical Product Specifications (GPS): Geometrical tolerancing Tolerances of form, orientation, location and runout
ISO/TS 12180-1:2003	Geometrical Product Specifications (GPS): Cylindricity Part 1: Vocabulary and parameters of cylindrical form
ISO/TS 12180-2:2003	Geometrical Product Specifications (GPS): Cylindricity Part 2: Specification operators
ISO/TS 12181-1:2003	Geometrical Product Specifications (GPS): Roundness Part 1: Vocabulary and parameters of roundness
ISO/TS 12181-2:2003	Geometrical Product Specifications (GPS): Roundness Part 2: Specification operators
ISO/TS 12780-1:2003	Geometrical Product Specifications (GPS): Straightness Part 1: Vocabulary and parameters of straightness
ISO/TS 12780-2:2003	Geometrical Product Specifications (GPS): Straightness Part 2: Specification operators
ISO/TS 12781-1:2003	Geometrical Product Specifications (GPS): Flatness Part 1: Vocabulary and parameters of flatness
ISO/TS 12781-2:2003	Geometrical Product Specifications (GPS): Flatness Part 2: Specification operators

Appendix 2 - Drawing Designation

Table 3: Typical parameter designations on drawings and/or instrumentation

ISO Nomenclature	Drawing Symbol	Name
RONt	○	Roundness Total
Runout	↗	Runout
Conc	◎	Concentricity
CYLt	⌭	Cylindricity
Total Runout	⌰	Total Runout
Coaxiality	◎	Coaxiality of an axis*
Coaxiality	Ⓘ	Coaxiality (ISO/DIN)
FLTt	▱	Flatness
STRt	—	Straightness
Parallelism	//	Parallelism
Squareness	⊥	Squareness

*Note that this symbol is also used for concentricity.

Appendix 3 - Glossary

Actual profile	The periphery of a cross-section of a part.
Alignment of axes	If one axis is in line with another, they are said to be in alignment.
Coaxiality	A measure of the disposition of a measured axis in relation to a datum axis.
Concentric	Two shapes are said to be concentric if they have the same center or if the two centers are identically positioned relative to an axis (i.e. a line drawn between the two centers is parallel to the axis).
Cylindricity	(More correctly departures from cylindricity). The amount by which a part departs from a perfect cylinder.
Eccentricity	The amount by which the centers of two shapes are displaced from one another in a single plane or, if in separated planes, relative to an axis.
Flatness	The distance separating two parallel planes that just enclose the profile under consideration.
Filter	An electrical circuit or software algorithm that reduces or suppresses those measured undulations that have spacing outside a selected range.
Gauge	(Sometimes called probe or pick-up). The embodiment of the electrical transducer, which converts movement of the stylus into electrical signals.
Least squares circle	A reference circle representing the average deviation of the profile from a true circle.
Lobe	When there are only a few undulations and these have approximately equal height and spacing, they are referred to as lobes.
Magnification	The amount of enlargement (in one direction.)
Maximum inscribed circle	The largest possible circle that can be drawn entirely inside a profile.

Measured profile	The representation of the profile obtained by a roundness measuring instrument.
Minimum circumscribed circle	The smallest possible circle that can be drawn entirely enclosing a profile.
Minimum zone circle	Two concentric circles enclosing the profile between them separated by the minimum possible radial distance.
Parallelism	The distance between two parallel lines or planes that are parallel to the datum feature and just enclose the profile under consideration.
Parameter	The type of value being measured.
Plug gauge circle	Same as the maximum inscribed circle.
Ring gauge circle	Same as the minimum circumscribed circle.
Roundness	(More correctly departures from roundness). The amount by which a part departs from a perfect circle.
Runout	The positional variation of the considered feature with respect to a fixed point during one complete revolution about the datum axis without axial movement.
Squareness	(More correctly departures from squareness). The amount (sometimes expressed as a gradient) by which a surface departs from being at right angles to an axis.
Straightness	(More correctly departures from straightness). The distance separating two parallel lines which just enclose the profile under consideration.
Stylus	That part of the instrument that contacts the surface being measured; generally a stylus tip fixed to a stylus arm is mounted to the gauge.
Undulations	The peaks and valleys on the periphery of a profile.

Recommended further reading

"Surfaces and their Measurement" by David Whitehouse. ISBN 1-9039-9660-0
The Taylor Hobson website at **www.taylor-hobson.com** has a helpful FAQ and glossary section.

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Serving a global market

Taylor Hobson is world renowned as a manufacturer of precision measuring instruments used for inspection in research and production facilities. Our equipment performs at nanometric levels of resolution and accuracy.

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