Introduction to the Measurement of Roundness

Introduction.

One of the most important fundamental forms for engineering components is the circular cross-section. Circular forms arise in many applications, particularly in bearing surfaces such as rotating shafts and ball bearing applications. The measurement of out-of-roundness (usually referred to simply as roundness) is an extremely important assessment. For example, a rotational bearing whose components are not accurately round will tend to be noisy and is likely to fail prematurely. Accurate roundness measurement is therefore vital to ensure correct function of these components.

The measurement of roundness is a vast topic. In this article I have outlined a number of common approaches to the measurement of roundness, highlighting some of their limitations.

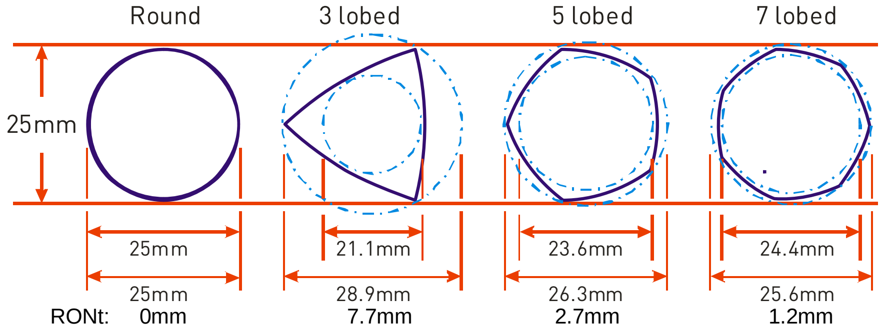
Diameter measurement.

Perhaps the first and simplest approach to gauging the roundness of a component is to measure the consistency of its diameter at a number of different orientations. This is often done in-process for checking machine set-up and can be adequate for assessing a component where the roundness is a cosmetic, rather than functional, requirement. It can be functionally relevant of course, and a good example of this is the UK fifty-pence piece shown in figure 1. One of the requirements for the coin is that it is able to be used in a coin-operated slot machine. The design as shown works very well in this application as it has a constant diameter. However it is clearly evident that the coin is not round.

Figure 1 - Diameter measurement of a coin.

At this stage it is useful to look at the ISO definition of roundness. Roundness is defined in ISO 1101 as the separation of two concentric circles that just enclose the circular section of interest. It is clear that measurement of diameter as shown above will not yield the roundness of the component in accordance with this definition.

To illustrate this, consider the diagram below. This shows a variety of components each having a constant measured diameter of 25mm. The size of the concentric circles that just fit inside and outside of the data are shown, and it is easy to see how markedly the roundness changes even though the diameters are the same for each component. These are clearly extreme cases, but they do serve to show the principle.



Vee-Block Method

Another method that is often used is to place the part in a vee-block and rotate it in contact with a dial gauge or similar indicator. This is essentially a three-point method rather than the two-point method above. If the part is truly round, with negligible irregularity, the pointer of the gauge will not move. Errors in the form will cause the dial indicator to show a reading, however the part will also move up and down as the irregularities contact the vee-block. Moreover, in the case of a shaft, the contact with the vee-block is not restricted to the plane being measured. This means that irregularities of the component along its length will affect the dial indicator reading.

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. For example, in the diagram below it can be seen that changing the Vee angle results in the irregularities being either in-phase (bump under dial gauge as the bumps contact the Vee) or out-of-phase (hollow under dial gauge as the bumps contact the Vee). In this circumstance the two set-ups will record different roundness values.

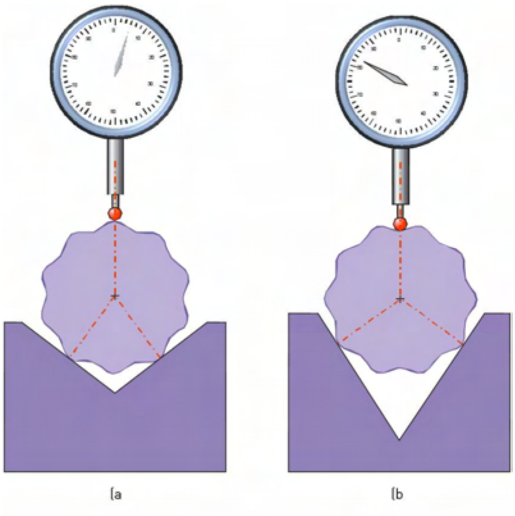


Figure 2 - Effects of changing the Vee angle.

Regardless of all its limitations, this method is still a practical, manual method for assessing roundness and is suitable for gaining an approximate roundness figure for a wide variety of applications. The technique can be readily adapted to the measurement of large components, including bores by integrating the dial gauge and Vee-block into a single unit.

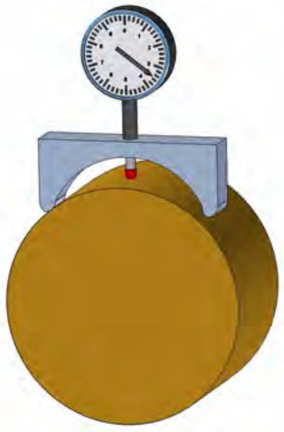


Figure 3 - Adaptation to measure large shafts.

Figure 4 - Adaptation to measure large bores.

Both of the fore-going methods are manual assessments of roundness. Automated measurements can be made using specialist equipment such as a co-ordinate measuring machine (CMM) or a dedicated roundness instrument.

Co-ordinate 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. A number of points are taken around the component and these are then combined in a computer to calculate the roundness of the component. Typically the number of data points is very small because of the time taken to collect them. As a result the accuracy of such measurements is compromised.

In Figure 5 the effects of measuring a very limited set of data points are easily seen. The same component is measured using just four probing points, the phases of which have been altered between the two diagrams. It can be seen that entirely different circles and centres are calculated as a result of the sparse data acquired. This is clearly a simplification and shown with an exaggerated roundness error to illustrate the point.

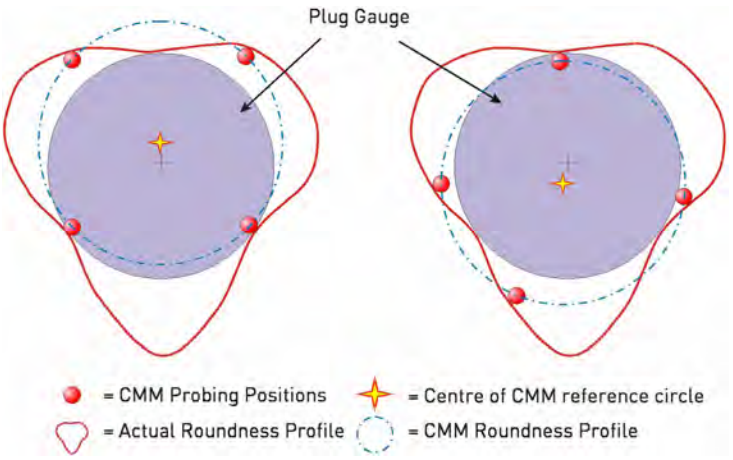


Figure 5 - Measuring roundness with few data points.

A further consideration is the accuracy of registering each point. Because the way data points are captured as the probe “triggers”, there is typically an uncertainty of position for each point that will be of the order of 1um or more. This will affect the uncertainty of the roundness measurement calculated by the measuring instrument.

An improved method (that has been available on these instruments for some years) is to replace the touch-trigger probe with a continuous scanning probe. This allows many thousands of data points to be acquired in a short period of time, overcoming the problem of sparse data shown above. The use of a scanning probe can also improve the measurement uncertainty as the probe is not continually being moved away from and back into contact with the component. However, problems still remain as the axes of the instrument are linear axes arranged in an orthogonal pattern. Because of this measuring around a circular feature requires two axes to be driven and requires a change in direction of those axes. Hysteresis at the turning points will cause relatively large errors in the measurement.

The way round this latter problem is to use a rotational datum to rotate the component whilst holding the gauge position stationary. This is the method employed by dedicated roundness instruments, and provides the most accurate way of measuring roundness. A number of CMM manufacturers are able to supply precision spindles and scanning probes as options on their instruments. However the cost of adapting a CMM in this way is often prohibitively expensive. A more cost-effective approach is often to use a dedicated roundness measuring instrument.

Rotational Datum Method

The most accurate method for determining roundness of a component is to measure the variation of radius from an accurate rotational datum using a scanning probe (one that remains in contact with the surface and collects a high-density of data points). A circle can then be fitted to this data and the roundness can then be calculated from knowledge of the component centre.

There are many dedicated instruments made for the measurement of roundness. The advantages of these instruments are that they can measure roundness extremely accurately in a short measurement time.

The most common configuration is a system that contains a rotating table onto which the component is mounted. This type of instrument is ideally suited to the measurement of circular features on components that have a cylindrical operational envelope, which is a very large proportion of components. An example of such an instrument is shown below.

Figure 6 - An example of a rotating workpiece roundness measuring instrument.

For other components, such as cylinder blocks and heads, connecting rods etc, an alternative approach is to use an instrument in which the spindle is used to rotate the gauge. Other (linear) axes are used to being the gauge into the appropriate feature of the component. One drawback of such a configuration is the limited reach that can be achieved. In order to overcome this, special extension tubes (known as “drop-arms”) are interposed between the end of the spindle and the gauge. Inevitably these drop-arms will contribute to measurement uncertainty, but this is not usually a problem compared to other techniques that could be considered. The following sequence of figures show an example of a rotating stylus type instrument – the Talyrond 450.

Another advantage of this type of system is that it is capable of taking much larger loads than those systems that rotate the workpiece.

Whichever method is used, a modern rotary datum roundness instrument will typically take many hundreds or even thousands of data points per revolutions of the spindle, for example the Talyrond 365 instrument is capable of taking up to 18000 points per revolution for roundness measurement. This high volume of data means that a number of different analyses, including filtering, slope analysis and harmonic analysis, can be obtained from the data.

Gauge resolution on these instruments is typically selectable from a number of ranges, and a resolution of the order of 1nm is available on a number of instruments. Overall measurement uncertainties, including the errors from the spindle, can be as low as 10nm for high-precision roundness systems. It is difficult to approach this kind of level of uncertainty without using a rotational datum.

Figure 7 - A Talyrond 450 measuring an engine block.

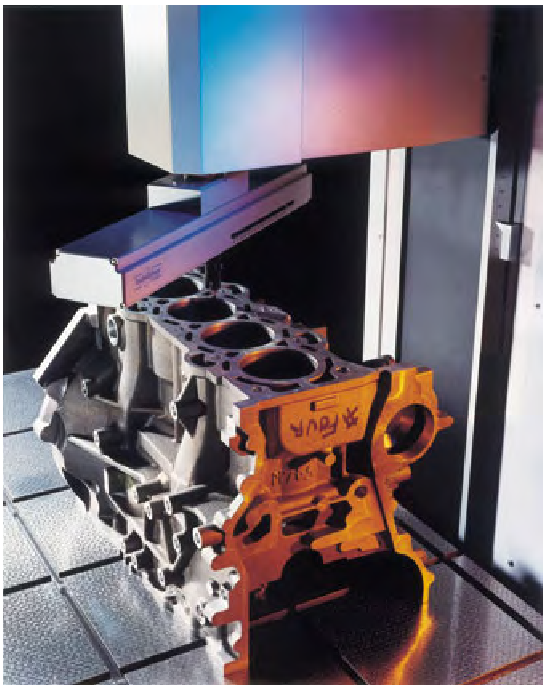


Figure 8 - Close-up of the measurement being made.

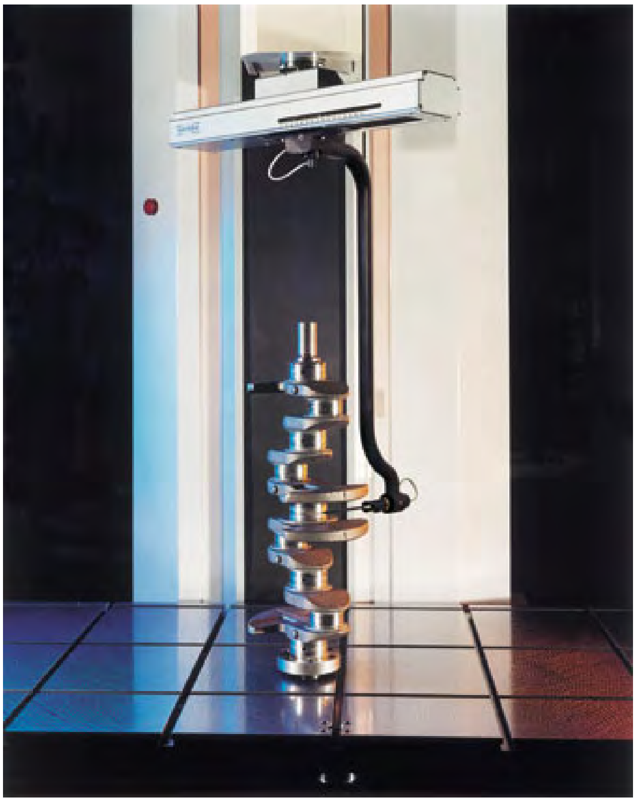


Figure 9 - Using a special drop-arm to measure a crankshaft.

Summary.

There are many approaches that can be taken for measuring roundness. Simple methods such as calliper measurements and dial-gauge measurements may be adequate for some circumstances, but the most accurate measurements are obtained using a rotational datum. Whilst a coordinate measurement system can be equipped with a rotational datum and continuous scanning probe, a more cost-effective solution is to use a dedicated roundness instrument.

There are two fundamental types of roundness instrument - the most common type being the rotating workpiece variety. This configuration is well suited to measuring components within a cylindrical operating envelope, such as fuel injectors, crank-shafts and other shaft and bore applications. The other configuration uses a rotating pick-up. This configuration is more suited to off-axis measurements, such as the measurement of cylinder bores and crank journals within a block and cam and valve-guide applications within a cylinder head, or for measuring large or unusual components.

Dr Mike Mills,
Chief Metrologist.