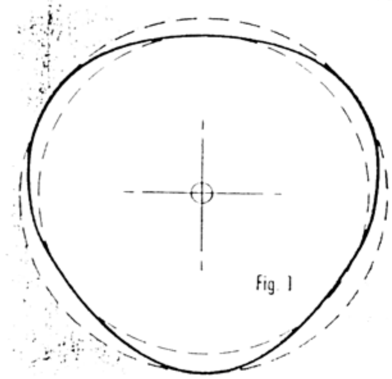
THE SHAPE OF THINGS TO COME

What do you do when you're doing everything right and it's still coming out all wrong? We had a case like this not too long ago, where a shop was making a spindle and bore assembly for a high precision application. The owner complained that while he was machining well within his specified -.0002 tolerance on the shaft, his parts were either causing excessive bearing loads, or worse, not fitting in the bores at all. "How can they be wrong," he said, "when everything measures right?"

What this fellow didn't realize was that there are more things which can go wrong with a part than dimension. Just as we cannot make parts perfectly to size, neither can we make them perfectly round or perfectly smooth. And, as we all move towards tighter and tighter tolerance machining, irregularities in shape and finish will have a greater and greater affect on our ability to make parts. This means we're all going to have to understand more about geometry and surface finish.

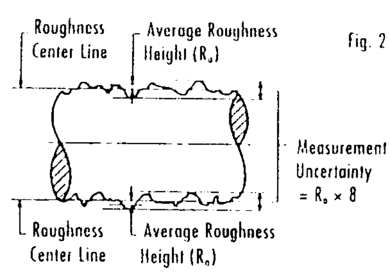
In the example above, analysis in our lab showed a consistent three-lobed out-of-round condition on the spindles which was making their effective diameters too large. Three-lobed out-of-round is very common when using centerless grinding, but it wasn't noticed in this case
because: 1) the specs didn't call for any geometric analysis on the parts; and 2) the shop was only using a two-point dimensional gage which was incapable of detecting the problem.

Figure 1 illustrates the relationship between out-of-roundness and effective diameter on a three-lobed part. As you can see, any two-point measurement will yield a consistent diameter, because each lobe is geometrically opposed by a flat area. This measured dimension would fall somewhere between the inner and outer dotted circles. However, the effective diameter, or the amount of space this part would actually require to clear, would be the outer dotted circle, which encompasses all the lobes. In this case, because the tolerance was so tight to begin with, the increase in effective diameter caused by the roundness problem exceeded his total tolerance for the part.



So did that mean he had to invest in a lot of fancy lab equipment, or buy a new centerless grinder? Fortunately not. As noted, out-of-round conditions with an odd number of lobes are common with centerless grinding (the greater the number of lobes, the more closely you approach true round), and once understood, are easily compensated for. In this case, a simple V-block fixture was set up with the blocks at 60° to measure the effective diameter, and the grinder set accordingly. Without going through the math involved, other odd-lobed out-of-round conditions can be similarly detected, using V-block fixtures set at other angles (108° for five lobes; 138_ 40' for seven lobes; and so on).

Unfortunately, in this case (but not for this column!) out-of-roundness was not the only problem. There was also a problem with surface finish which, while specified, was not really being measured. The specs called for an average roughness (R_a) of no more than 4 µin., but when measured, the parts showed an R_a of between 15 µin. and 25 µin. Since the affect of roughness on overall tolerance is a factor of at least 8, and sometimes as much as 20 (see Fig. 2), the 25 µin. of roughness took up the entire .0002" tolerance range on these parts!



Again, the solution was not costly equipment -- surface finish gages are readily and economically available for shop floor use -- but an awareness of the problem and an understanding of the basic causes. A simple redressing of the wheel solved the problem here, and allowed our shopowner to resume his normal sleeping pattern at night.

But the lesson is an important one. A recent report by the National Center for the Manufacturing Sciences showed that machining tolerances have decreased by a factor of five within the last decade, and that even tighter tolerances are on the horizon. This means that things like geometry and surface finish are going to play an increasingly important role in machining operations. And we need to understand that role, if we are to continue to produce good parts. That's the shape of things to come.

ROUNDNESS GAGING -- APPROXIMATELY

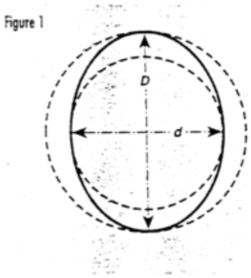
In a previous column we discussed the relationship between part geometry (i.e., roundness) and dimensional tolerance. Circular geometry gages, with their precision spindles, are the best -- and the standard -- method for measuring out-of-roundness. But these can be elaborate pieces of equipment and are usually confined to applications where a very high degree of accuracy is required concerning part geometry.

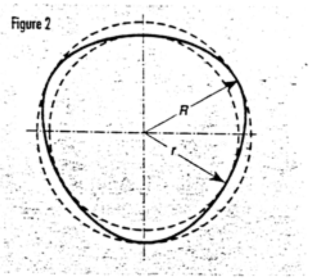
Most jobs, however, have fairly simple requirements for roundness. While a true roundness measurement requires a complex description of the geometric and dimensional relationships of dozens or hundreds of points on a diameter, most job specifications simply call for parts to be "round within 0.XXXX in. variation in radius." In other words, as long as no point on the radius falls outside of two concentric circles, the actual shape of the surface is secondary.

This being the case, there are ways to approach the problem of roundness measurement that can provide a pragmatic, low-cost alternative to the circular geometry gage. Although these methods rarely give a technically accurate measurement of roundness, they are often close enough to give a good indication of the functional implications of an out-of-round condition. If you understand the nature of your out-of-roundness, it may be possible to qualify the part using conventional equipment such as a micrometer, bore gage, comparator stand or a V-block arrangement.

Understanding the geometry involved is the key. Generally speaking, out-of-roundness is either symmetrical, involving regular or geometrically arranged lobes or points on the part's circumference, or asymmetrical, where the lobing is not regular. Most machining processes create symmetrical lobing, producing either an even, or an odd number of lobes. Even-number lobing is sometimes seen in precision boring operations, caused by a worn or out-of-balance spindle. Odd-number lobing may be caused by a 3-jaw chuck (producing a 3-lobed workpiece), or a centerless grinder (which may create a 5-lobed condition). Asymmetrical lobing cannot be measured by the means described here. It is evidenced by irregular travel of an indicator, and is usually indicative of a problem in the tool.

In cases where an even number of lobes is arranged geometrically on the part, each lobe is opposed by one diametrically opposite (see Figure 1). The piece, therefore, will have major and minor diameters. Knowing this, we can gage the part using simple two-point, or diametrical measurement methods. The difference in the differential measurements will generally be twice the out-of-round value due to the diametral versus radial method of assessment. For example, if our specs call for a part that is "round within 0.0001 in. variation in radius," we can measure using a simple comparator, and reject any part where the Total Indicator Reading (TIR) is larger than 0.0002 in.





Parts with an odd number of lobes pose a slightly more complicated problem. As shown in Figure 2a, where an odd number of lobes exist, each lobe is diametrically opposed by a flat area. These parts can be measured on a V-block fixture, using the following formulae to establish the included angle of the V-block, and the multiplication factor. (Illustrated in Figure 2b):

1) Included angle:

$$2ø = 180 - 360/n$$

Where "ø" equals half the included V-block angle, and "n" equals the number of lobes.

2) Multiplication Factor:

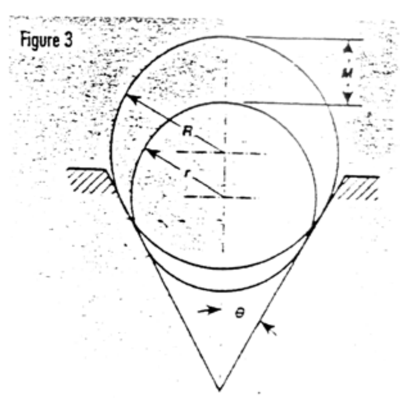
$$M = (R + R \csc ø) - (r + r \csc ø)$$

or

$$M = (R - r)(1 + \csc ø)$$

Where "M" equals the measured difference (as shown on the indicator), "R" equals the radius of the circumscribed circle, "r" equals the radius of the inscribed circle, "ø" equals 1/2 the included angle of the V-block, and "R - r" equals the specified radial variation (tolerance) for the part.

Quality Gaging Tips . . .



This can be simplified. The table below, worked out from these formulae, gives the required multiplication factor and included V-block angle for 3-, 5-, and 7-lobed conditions, which represent the majority of the odd-lobed conditions found in normal machining practice.

Condition	**Multiplication Factor**
Three lobes	3.00
Five lobes	2.24
Seven lobes	2.11

Let's use a specific example. The part is specified to be "round within 0.0001 in. variation in radius." We know the part was produced on a CNC lathe using a 3-jaw chuck, and we have previously determined (possibly through the use of a circular geometry gage on a short-term basis) that the process generates a 3-lobed condition. Therefore, we use a gage having a V-block fixture set up with a 60-degree included angle. To determine allowable variation in radial out-of-roundness, multiply 0.0001in. x 3. Any TIR larger than 0.0003 in. is therefore out of tolerance.

Bearing in mind that such measures are only approximate, these techniques provide a good, practical means to determine out-of-roundness on the shop floor.

CIRCULAR GEOMETRY GAGING MEANS MORE THAN ROUNDNESS

Previously, we looked at the measurement of out-of-roundness. But roundness is far from the only circular geometry specification that machinists may be required to meet and, therefore, to inspect. Let's look at some of the other parameters. As we describe them, refer to the figure to see how each is indicated on part print callouts.

Roundness involves no datum: it is evaluated relative to the part profile itself, using one of the four methods discussed last month (Maximum Inscribed Circle, Minimum Circumscribed Circle, Least Squares Center, or Minimum Radial Separation). Eccentricity, in contrast, is measured relative to a datum, which is the center of part rotation, as established by the spindle of the geometry gage (or by a part feature defined as the datum that has been centered on the spindle). Eccentricity is the distance between the center of the reference circle used to calculate out-of-roundness, and the datum. As the part rotates 180° around the datum axis, the center of the reference circle is displaced by twice the eccentricity value: hence, concentricity is twice eccentricity. Both eccentricity and concentricity may be measured for features lying in a single plane, or in two planes.

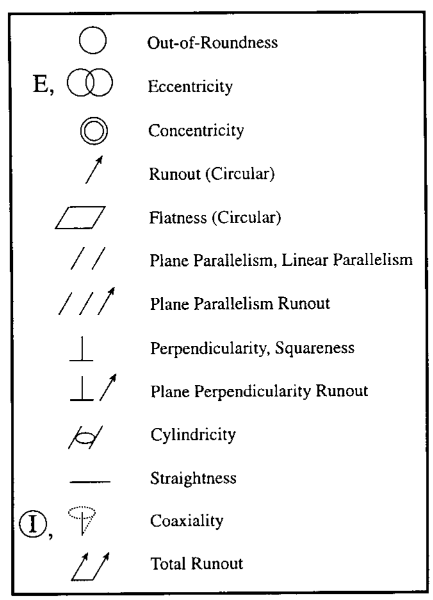
Circular runout, another datum-referenced measurement, measures the radial separation of two concentric circles whose common center is the datum, and which entirely enclose the part profile. Circular runout is the result of the combination of two form-error factors: out-of-roundness, and out-of-concentricity. The two factors may be additive or may cancel each other out, depending on vector directions. Circular flatness (of a flange, for example) may be specified at an indicated radius, and measured in a circular trace. This is a datum-free measurement that uses either a minimum-zone or least-squares calculation, similar to those used in roundness measurements.

Circular flatness can be used as the basis for plane parallelism measurements. Care must be taken, however, in reading and interpreting callouts correctly. The statement "A is parallel to B" (within a specified tolerance) implies that surface B is the datum. Any out-of-flatness present in this surface is ignored, while out-of-flatness in surface A is included in the calculation. The gage user cannot treat the two surfaces interchangeably. If one excludes out-of-flatness of both surfaces, the measurement is defined as parallelism plane runout.

In order to measure a number of squareness-related parameters, a vertical datum axis must first be established by measuring the roundness of the part at two planes, thus creating a part axis between the centers of the two reference circles. After normalizing the part axis to the gage spindle's axis of rotation, the horizontal surface in question is gaged at a specified radius, and normalized to the datum axis. Perpendicularity includes the out-of-flatness of the horizontal surface, while perpendicularity plane runout ignores out-of-flatness. Squareness is defined as half the plane runout value—in other words, it measures only from the center of the part's rotation to the indicated radius, while perpendicularity plane runout measures the deviation across the entire circle.

All of the parameters above can be measured on so-called "roundness" gages, which do not provide a means for precision vertical movement of the gage head. "Cylindricity" gages, on the other hand, incorporate precision reference surfaces in the gage head positioning axes, permitting measurements of a number of additional parameters.

Cylindricity is a useful parameter that provides an overall assessment of part roundness, taper, and straightness. Because it is not possible to measure every point on a three-dimensional surface, part profiles are taken at a number of planes, then combined into a single cylindricity value. Statistical analysis, and experience, may be required to establish the number of sample profiles needed for an accurate measurement.



Cylindricity gages can also be used to measure the straightness of an ID or OD surface on a vertically oriented workpiece, by keeping the part stationary and traversing the gage head up or down. Straightness can then be used as the basis for linear parallelism measurements, comparing opposed ID or OD surfaces, or comparing an ID surface to an OD surface.

We haven't space here to describe additional, complex parameters such as coaxiality and total runout. The main point Alex wishes to make, however, is that numerous parameters have been developed in order to control the functionality of parts across a wide range of possible configurations and applications. Make no assumptions when gaging part geometry: be sure you understand what the parameter means before you try to measure it. A couple of useful reference sources are: *Geo–Metrics II* by Lowell W. Foster (Addison Wesley Publishing); and the ANSI B89.3.1 standard for out-of-roundness measurement.

GEOMETRY GAGING PART II: FOUR METHODS OF MEASURING OUT-OF-ROUNDNESS

We have introduced the subject of circular geometry gaging by looking at the instrumentation, and we noted that one reason for the recent proliferation of geometry gages is the use of personal computers as gage controllers. The PC has greatly simplified geometry measurements by speeding up the calculations involved. Now, let's proceed to the most common geometry measurement, and the basis for most circular geometry parameters: roundness, also known as out-of-roundness or circularity. As we'll see, even "simple" roundness has benefitted greatly from the processing power of the modern PC.

Ideal roundness, according to ANSI standard B89.3.1, is "the representation of a planar profile all points of which are equidistant from a center in the plane." Out-of-roundness, then, is "the radial deviation of the actual profile from ideal roundness," and the out-of-roundness value (OOR) is "the difference between the largest radius and the smallest radius of a measured profile; these radii are to be measured from a common point... ."

To measure out of roundness, then, it is necessary to compare the part profile to an ideal circle or datum. But since the part profile itself isn't round, how do you locate the ideal circle?

Four methods are in common use. Many modern geometry gages offer users a choice. Typically, the user selects the required method, then initiates the measurement on the gage. The gage rotates the part and collects data, which it presents in the form of a polar chart. Then the computer controller uses one of the following methods to locate the center of the reference circle:

Maximum Inscribed Circle (MIC): the center of the largest circle that can fit within the measured polar profile. This method is used only for geometry measurements of inside diameter features.

Minimum Circumscribed Circle (MCC): the center of the smallest circle that fits around the measured profile. This method is used only for outside diameter features.

Least Squares Center (LSC): the center of a circle, of which the sum of the squares of the radial ordinates of the measured profile is the least possible number. This method is used for both ID and OD features.

Minimum Radial Separation (MRS): the center of two concentric circles which, with the least possible separation, contain all points of the profile. This method is also used for both ID and OD features.

Different part applications typically call for different measurement methods. For example, when the geometry of an inside diameter is specified, the presence of burrs, dirt, and other "high points" on the ID are typically of critical concern, while low points (e.g., scratches) are not quite as important. Accordingly, inside diameters can be measured using the MIC method, because it is quite sensitive to high points, and relatively insensitive to low points. In other words, a burr will cause a significant shift in the location of the center, while a scratch will cause only a minor shift.

On the other hand, scratches tend to be of greater functional concern on outside diameter parts, while burrs tend to be of less importance. The MCC method, which is sensitive to scratches, and insensitive to burrs and dirt, therefore has advantages for measuring outside diameters.

The MRS method is quite sensitive in equal measure to both positive and negative asperities (i.e., burrs and scratches) and typically generates the largest OOR value of the four methods. The LSC method, in contrast, is relatively insensitive to extreme asperities of both kinds, and therefore generates the most stable center and the smallest OOR values of the four methods. As both of these methods react equally to positive and negative asperities, they tend to be useful for measuring mating ID and OD parts. And because most ID parts do have a mating OD part (and vice versa), the MRS and LSC methods are in more frequent use than the MIC and MCC methods.

OOR values may differ by as much as 10-15% from the same measurement data, depending on the method used. Inspectors must refer to the part print callout before firing up the gage.

The use of the proper reference circle has importance beyond just OOR measurements: many other parameters are based on roundness and the location of the circle's center, and they too will be influenced by the method selected. Concentricity, circular runout, total runout, coaxiality, and cylindricity are all affected. Now, aren't you glad the gage controller will run the calculations for you? (Some gages even allow the user to store the data, and then apply the different measurement methods on a post-process basis.)

If the part print callout doesn't specify the method, MRS is the default, according to ANSI, even though LSC is in more common use. My colleague Alex has qualms, therefore, about the use of a default. If the method isn't shown in the callout, you never know if the engineer intended that the default method be used, or if he simply forgot to take it into consideration. Alex therefore recommends that engineers use the ISO convention, which requires that the method be specified. It's certainly not a lot of extra trouble to add the information to the callout, and it may help avoid unnecessary confusion.

AIR RINGS, CMMS AND SUPERMIKES

A major aerospace customer complained that the air-ring gage we sold him was inaccurate. How did he know, I asked. Because, he said, he checked the measurements against a coordinate measuring machine and a supermicrometer he had in the shop. The CMM and the supermike agreed with one another closely, while measurements on the air gage differed from them by as much as .0004", ergo...

"Send me a few samples," I told him. "and we'll check them in our lab, where results are good to one millionth. Then we'll know exactly what size they really are, and which gage is at fault."

The lab identified at least part of the problem even before they put them on a gage. "Where are the witness marks?" they wanted to know. "Where, exactly, were these parts measured?"

"What difference does it make?" asked the customer. "They're simple OD cylinders."

In fact, it makes a lot of difference. If a part is slightly out-of-round, then the measuring method you choose will influence your measurement. A CMM, for example, will tend to average out errors of geometry and waveform. A supermike might give you the min, the max, or somewhere in-between, depending upon precisely where the measurement is made. The performance of an air ring can also vary between min/max and average reading, depending upon the number of jets, the part's geometry and surface finish, and the position of the part in the gage. None of them are necessarily wrong.

In this particular case, all three gages were giving accurate readings, but each one was measuring different dimensions. In the lab, we found that the parts exhibited geometry errors of as much as .0003", in addition to a small amount of waveform error. By measuring at different locations on the parts, the manufacturer sometimes picked up on that variation, and sometimes missed it. Simply by measuring from a consistent datum, we brought the air gage readings to within 50 millionths of the other two gages.

Instead of asking "is it accurate?" we should be asking "is it appropriate?" Most gages are accurate as delivered from the manufacturer, but every gage embraces certain limitations and assumptions. When selecting a gage or a gaging method, it is essential to establish a clear objective: Do you want to account for, or ignore, variation due to geometry, waveform, and surface finish? Do want to know the maximum OD of a part, or the minimum OD, or the average OD?

The answer to these questions depends upon the application. As a hypothetical example, consider a spool valve assembly, in which the bore is a perfect cylinder, and the spool itself has a slight three-lobed condition. The overall (average) diameter of the spool may determine the efficiency of the valve, but its maximum diameter will determine whether the two parts can be assembled or not. It's up to the user to determine which is the critical measurement, and then select the measuring tool most appropriate to the task.

Many gages offer a certain degree of flexibility. For example, it may be possible to specify the arrangement of jets in an air ring to automatically give the min/max, or average reading. Likewise, it may be possible to program a CMM to account for geometry factors. But before you can do either, you have to know what you want to measure.

Not surprisingly, this situation is paralleled by the factor of surface finish. Air gages tend to average, or ignore, surface roughness -- up to a point. A supermike, measuring on the "peaks," will tend to maximize its effect, while a CMM will randomize peaks and valleys, generally giving an average. In the aerospace manufacturer's case, we found that surface finish accounted for the remaining difference in readings between the gages.

And if that isn't complicated enough, here are two more factors you might want to consider: 1) The geometry of the gage's sensitive contact and holding fixture may affect measurements. 2) Masters are also machined parts that are subject to the influences of geometry and surface finish.

Why didn't we worry about this stuff before? Because even as recently as 10 years ago, tolerances were generally looser. But as tolerances get tighter, variations in part geometry and surface finish exert proportionally more influence on our measurements.

Fig. 1

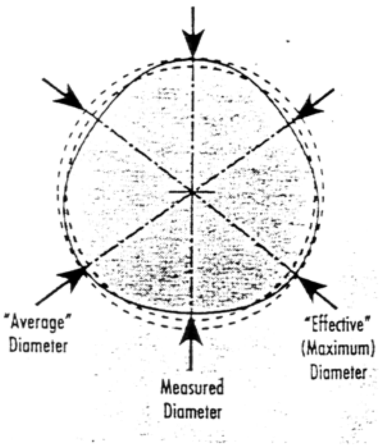
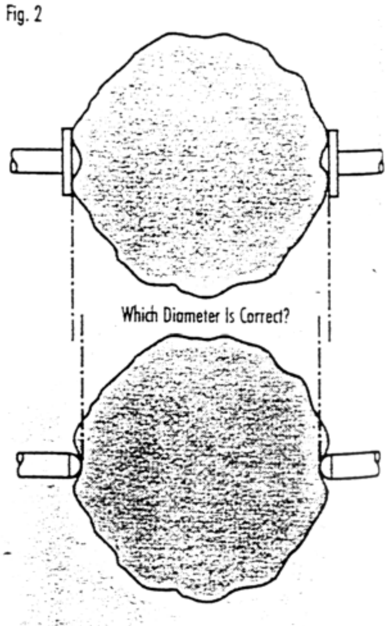

"Average"
Diameter
"Effective"
(Maximum)
Diameter
Measured
Diameter

Fig. 2


Which Diameter Is Correct?