

# UNCERTAINTY ASSESSMENT FOR THE ROUNDNESS MEASUREMENT OF CRANKSHAFTS USING A VIRTUAL GAGING SYSTEM

Xianping Zhang and Addison D. Cole  
ADCOLE CORP.  
Marlborough, MA 01752

## **Introduction**

Crankshafts are one of the critical components in reciprocating engines, and their accuracy greatly affects the fuel consumption, dynamic performance and reliability of the engines. Adcole Corporation's Cylindrical Coordinate Measuring Machines (CCMMs) are specifically designed for measuring crankshafts of reciprocating engines. Many parameters including the roundness, diameter, cylindricity and straightness of journals and parallelism and perpendicularity among the journals can be measured during one set-up.

In this paper, we attempt to assess the uncertainty of roundness measurement of crankshaft journals using a virtual gaging system we reported earlier <sup>1</sup>. The virtual gaging system is basically a mathematic model of the real gages, and each data point is obtained by actually moving the follower and part models and mathematically detecting the contact condition. By varying the errors of different components, we can assess the uncertainty of roundness measurement through simulations using the virtual gaging system. In the following, some factors affecting the roundness measurement uncertainty are discussed first. Then the uncertainty assessment is demonstrated through examples. It is shown from demonstration that assumption of normal distribution is inappropriate for uncertainty assessment of roundness measurement, and uncertainty assessment using virtual gaging system gives better result.

## **Some Factors Affecting the Roundness Measurement Uncertainty**

The roundness is a type of form error of circular shapes such as crankshaft journals, and the factors affecting the uncertainty in the roundness measurement is much more complicated. Currently the common practice is to use a single number such as total indicator reading (TIR) to represent the roundness, and this is in accordance with the national standards such as ANSI Y14.5M <sup>2</sup>. In the following, we will discuss some factors that affect the roundness measurement uncertainty of crankshaft journals. The factors to be discussed include the assumption of normal distribution, measurement method, sampling scheme, spindle error motion, and follower straightness error.

*Assumption of Normal Distribution:* In the assessment of measurement uncertainty, normal distribution is often assumed to derive the expanded uncertainty of the final results. This is true for many applications, but it falls apart when it is assumed for applications such as roundness measurement uncertainty assessment. The problem is that under normal distribution, the uncertainty interval extends on both sides of the mean value in order to include all the probable values; while in roundness measurement, we know that the roundness of a perfectly round part will be zero, which is the lower bound of the uncertainty interval. Therefore, using assumption of normal distribution would lead to erroneous expanded uncertainty for roundness measurement result.

*Effect of Methodology:* This means how the roundness data are collected and processed. For instance, in the roundness measurement the data points may be collected using two diametrically opposing probes. This method actually measures the diametric variation of the cross section, and it will not reveal the odd-lobed shapes. In other word, for any odd-lobed shapes it will look perfectly round. Adcole gages measure the radial variation and will reveal both odd and even-lobed shapes.

*Sampling Scheme:* Sampling scheme normally includes the number of sampling points and their distribution, and is a critical factor affecting the roundness measurement error in crankshaft journals. In Adcole gages, the sampling points are uniformly distributed along the whole circle of the cross section being measured for a journal, so in the following the different sampling schemes will only mean the different number of sampling points. Assume that the journal has a three-lobed shape and the journal is sampled with three points uniformly distributed around the journal. Then, we can see that the journal will look perfectly round even though it is not. According to sampling theorem, in order to reveal the three lobes of the journal, the number of sampling points has to be at least six. In order to measure higher frequencies, the number of sampling points has to be large enough. Many CMMs equipped with

only touch trigger probes are limited by the maximum number of sampling points and consequently have a very limited frequency response for roundness measurement. In Adcole gages, the number of sampling points is up to 3600; therefore, the maximum number of detectable lobes, according to the sampling theorem, can reach 1800. This is very useful when the detection of high harmonics is important such as chatter analysis.

*Spindle Error Motion:* Spindle error motion causes a perfectly round journal to look non-round. This is true for all roundness measuring instruments. In Adcole gages, the spindle error motion has the maximum effect at the headstock end and the minimum effect at the tailstock end. If no other error sources exist, the roundness of the journal at the headstock end would be approximately the same as spindle error motion.

*Follower Straightness:* In Adcole gages the follower is the component in contact with the part being measured, and the coordinates of the contact points are recorded during the rotation of the part. For main journals the contact points on the follower are within an extremely small region so the follower form error can be neglected. However, when pin journals are measured the contact points are distributed along the follower, and therefore the follower form error (straightness) will be mapped to the roundness of the journals if it is not corrected. In Adcole gages the follower straightness is strictly controlled and can also be compensated in the software, so the uncertainty of the roundness measurement for pin journals can be minimized.

There are also other factors affecting the roundness measurement. The factors include, but not limited to, vibration and gravitational effects, and so on. These factors will not be discussed here.

### **Uncertainty Assessment of Roundness Measurement Using A Virtual Gaging System**

In uncertainty assessment of roundness measurement using virtual gaging system, the error sources are varied and combined and then plugged into the virtual gaging system to produce the roundness result of journals. For each input error source, the standard uncertainty is assigned with either a type A uncertainty or type B uncertainty according to the ISO document, "Guide to the Expression of Uncertainty in Measurement" (GUM)<sup>3</sup>. Uncertainty of roundness is obtained from the output of the virtual gaging system. In the following, we will demonstrate the process of uncertainty assessment through examples, and show the inappropriate assumption of normal distribution for roundness measurement.

#### *Example 1*

In this example, we will show a general but very simple case. This case also applies to other roundness measuring instruments. The part will assume a 2nd harmonic roundness error, and the gage also has its only error in the spindle and it assumes a 2nd harmonic error motion in the measurement direction. We will also assume the spindle error motion is repeatable, which indicates that it is fixed in the gage coordinate system. It is obvious that the roundness data can be analytically expressed as follows:

$$r(\theta) = e_p \cos(2\theta - \phi_p) + e_s \cos(2\theta - \phi_s) \quad (1)$$

where,  $e_p$  is the amplitude of the 2nd harmonic of part roundness error,  $e_s$  is the amplitude of the 2nd harmonic of spindle error motion,  $\theta$  is the angle position in the gage coordinate system,  $\phi_p$  is the phase of the part error and  $\phi_s$  is the phase of the spindle error. The right side of the above equation can be simplified as

$$r(\theta) = [e_p^2 + e_s^2 + 2e_p e_s \cos(\phi_p - \phi_s)]^{1/2} \cos(2\theta - \alpha) \quad (2)$$

where  $\alpha$  is the resultant phase. The measured roundness value is then

$$e_r = 2[e_p^2 + e_s^2 + 2e_p e_s \cos\phi]^{1/2} \quad (3)$$

where  $\phi = \phi_p - \phi_s$ . This indicates that the measured roundness value varies as the phase relationship between the part form error and the spindle error motion changes. The measured roundness value will fall within the interval of

$[2|e_p - e_s|, 2(e_p + e_s)]$ . Now let us assess the roundness uncertainty from a common procedure. We will repeat the measurement process 10000 times, record the roundness each time, and then calculate the mean and standard deviation of the roundness values from these 10000 measurements. We will let the virtual gaging system do the job. Assume that the amplitude of the 2nd harmonic of the part form error is  $2 \mu\text{m}$ , the amplitude of the 2nd harmonic of the spindle error motion is  $0.15 \mu\text{m}$ , and the phase difference,  $\phi$ , uniformly varies from 0 to  $2\pi$ . The uniform distribution of  $\phi$  simulates repeated roundness measurement process since in the repeated measurement the part is repositioned on the gage and then the phase difference  $\phi$  could be anywhere from 0 to  $2\pi$ . Substituting these parameters into the virtual gaging system, we obtain the following result from one simulation:

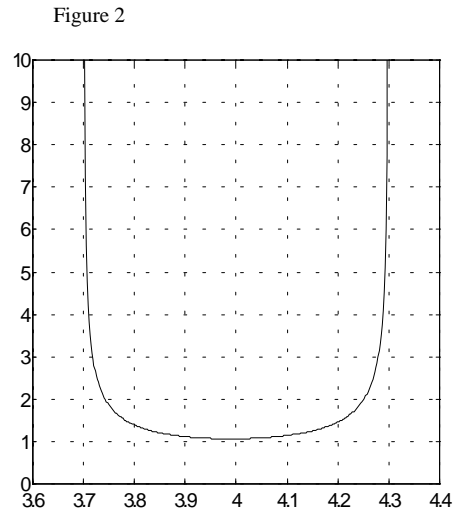
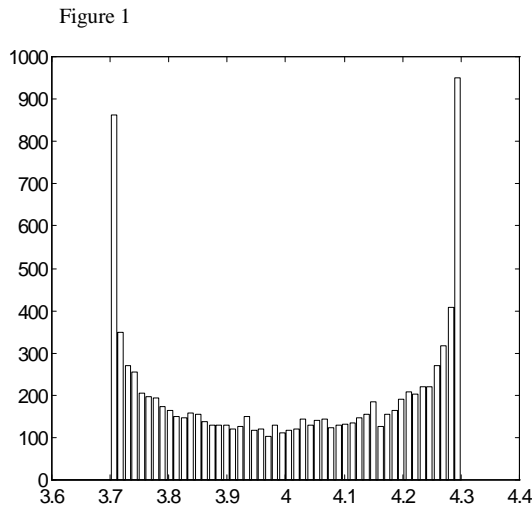
$$\text{max} = 4.3 \mu\text{m}; \quad \text{min} = 3.7 \mu\text{m}; \quad \text{mean} = 4.009 \mu\text{m}; \quad \text{std} = 0.213 \mu\text{m}.$$

If the minimum and maximum values are used for the roundness uncertainty, we conclude that the roundness values will fall within the interval of  $[3.7\mu\text{m}, 4.3 \mu\text{m}]$ . However, if we assume normal distribution and use a coverage factor of 3, we will obtain an interval of  $[3.370 \mu\text{m}, 4.648 \mu\text{m}]$ . Comparing the two intervals, we find that the second one is more than two times wider than the first one. Obviously the normal distribution is not applicable in this case. Figure 1 shows the histogram of this 10000 simulated results and it is clearly seen that the distribution is not normal. On the other hand, the interval obtained using the maximum and minimum values is the same as the one obtained from the analytical result. This example shows that using the virtual gaging system gives a better uncertainty assessment and it might be true for other cases.

Since this is a simple case, it is easy to show that when uniform distribution is assumed for phase difference  $\phi$  the probability density of the roundness  $e_r$  can be expressed as following:

$$p(e_r) = \frac{2e_r}{\pi} [(8e_p e_s)^2 - (e_r^2 - 4e_p^2 - 4e_s^2)^2]^{-1/2} \quad (4)$$

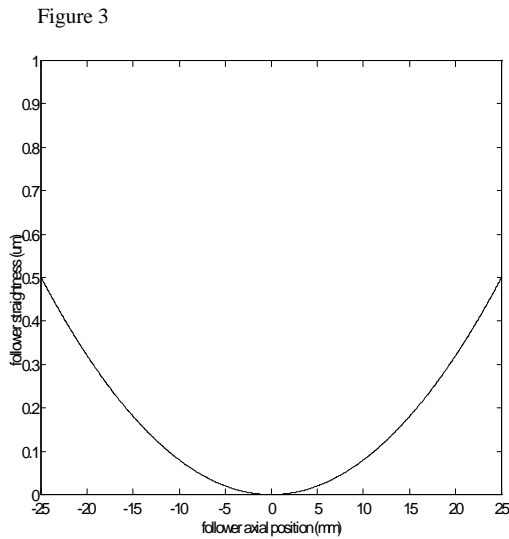
and for the parameters given in the example, the probability density is plotted in Figure 2. Note that at the lower and upper bounds, the distribution density goes to infinity. Comparing Figure 1 and Figure 2 we find that the simulation using the virtual gaging system gives the correct distribution for roundness uncertainty.



### Example 2

In this example, in addition to the part form error and spindle error motion, follower straightness error is also considered. In the simulation we will assume  $0.5 \mu\text{m}$  of follower straightness in a 50-mm span as shown in Figure 3. Two cases are compared; one case is with the follower straightness correction enabled and the other with the

follower straightness correction disabled. The variation of roundness measurement is still due to the random initial phase position of the part, which is assumed to have a uniform distribution within  $[0, 2\pi]$ .



The simulation result using the virtual gaging system is summarized in Table 1. It is seen that both cases give the same range ( $0.6 \mu\text{m}$ ) and standard deviation ( $0.212 \mu\text{m}$ ). However, the mean, minimum and maximum values differ between the two cases. When the follower straightness correction is enabled, the interval of  $[3.7\mu\text{m}, 4.3\mu\text{m}]$  is obtained, which includes the true roundness of the part ( $4 \mu\text{m}$ ); while the follower straightness correction is disabled, the interval then is  $[3.276\mu\text{m}, 3.876\mu\text{m}]$ , which does not include the true roundness of the part ( $4\mu\text{m}$ ). This indicates that in order to accurately assess the roundness uncertainty, the known systematic effects should be corrected. This agrees with the ISO GUM. The histograms of these simulations have the similar shape as the one in Example 1; therefore, the distribution is also not normal in these cases.

However, if normal distribution is assumed, the assessed uncertainty will be larger than that obtained directly from the simulation.

Table 1: Summary of Simulation Result (Unit:  $\mu\text{m}$ )

Case	Min	Max	Range	Mean	Std
Follower Straightness Correction Enabled	3.7	4.3	0.6	4.006	0.212
Follower Straightness Correction Disabled	3.276	3.876	0.6	3.582	0.212

### Closing Remarks

Normal distribution is usually assumed to assess the uncertainty in dimensional measurement results. This assumption is quite accurate for many applications such as in diameter measurement. However, when it comes to roundness measurement, it falls apart since the roundness has no negative values. This is true for similar applications such as parallelism, perpendicularity, cylindricity, and so on. We demonstrated using virtual gaging simulation that the roundness distribution is far different from normal, and that the assumption of normal distribution would give much larger roundness uncertainty. The examples also showed that using the virtual gaging system might be able to directly give better results in uncertainty assessment. When more error sources are involved in the measurement process, it is probably easier to assess uncertainty using virtual gaging than using other means such as building an accurate mathematical model and then propagating the uncertainty according to the law of propagation of uncertainty.

### References

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