Evaluation of Uncertainty in Cylindricity Measurement based on Coordinate Measuring Machine

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Abstract. According to the measurement method of cylindricity based on coordinate measuring machine (CMM), establish a black box evaluation model for the uncertainty of CMM cylindricity measurement, and analyze the sources of various uncertainties. Based on measurement examples, this paper elaborates on the evaluation process of cylindricity measurement uncertainty based on CMM, calculates the extended uncertainty based on CMM, and provides reference for the evaluation of cylindricity measurement uncertainty in CMM.

Keywords: metrology; coordinate measuring machine; cylindricity; uncertainty in measurement.

1. Introduction

Coordinate Measuring Machine (CMM) is a precision geometric measurement instrument that can quickly and accurately measure geometric quantities such as dimensions and positional tolerances of components. Due to the variety of sources of measurement uncertainty based on CMM measurement, the construction of uncertainty models is complex, and the uncertainty components are difficult to accurately quantify, resulting in difficulty in evaluating measurement uncertainty. To address the assessment of measurement uncertainty in CMM for specific tasks, relevant scholars have conducted research. Reference [2] studied the uncertainty analysis method for size measurement based on CMM, constructed a black box model for evaluating measurement uncertainty, and used measurement system analysis methods to quantitatively analyze the uncertainty components introduced by six characteristic indicators of measurement values. Reference [3] studied the evaluation of measurement uncertainty of CMM in product inspection using measurement system analysis method. Reference [4] studied the uncertainty assessment of shape measurement tasks based on CMM, achieving fast and reliable uncertainty assessment of CMM shape measurement. To further standardize and guide the evaluation of measurement uncertainty in CMM, the national standard [5] GB/T 24635.1-2020 provides technical guidelines for determining measurement uncertainty in CMM. On the basis of the aforementioned research, this article focuses on the evaluation of cylindricity measurement uncertainty based on CMM for cylindricity measurement tasks.

2. Measurement model

Cylindricity belongs to the form error in geometric errors, which refers to the variation of the actual measured cylinder facing its ideal cylindrical surface[6]. The evaluation methods for cylindricity include the minimum enclosing area method, least squares method, minimum circumscribed method, and maximum inscribed method. When using CMM for cylindricity measurement, based on the representation of the input and output of cylindricity measurement, a black box modeling method based on quantity characteristic analysis is adopted to establish the following model

$$r = R + \delta_1 + \delta_2 + \delta_3 \tag{1}$$

where, r is the cylindricity measurement result, R is the estimated value of cylindricity, δ_1 is the impact of CMM detection error on measurement results, δ_2 is the impact of cylindricity measurement repeatability on the measurement results, δ_3 is the impact of cylindricity measurement reproducibility on measurement results. δ_1 is a uniform distribution with an expected value of 0, and the standard deviation is the uncertainty u_1 introduced by the CMM detection error. δ_2 is a normal distribution

with an expected value of 0, and the standard deviation is the uncertainty u_2 introduced by measurement repeatability. δ_3 is a normal distribution with an expected value of 0, and the standard deviation is the uncertainty u_3 introduced by measurement reproducibility.
According to the measurement model equation (1), ignoring the correlation between components, the formula for calculating the uncertainty of the composite standard is

$$u_c^2(r) = c_1^2 u^2(\delta_1) + c_2^2 u^2(\delta_2) + c_3^2 u^2(\delta_3) \tag{2}$$

where, c1 is 1, c2 is 1, c3 is 1.
Then

$$u_c(r) = \sqrt{u^2(\delta_1) + u^2(\delta_2) + u^2(\delta_3)} \tag{3}$$

3. Evaluation of measurement uncertainty

3.1 Measurement example

Under laboratory environmental conditions, CMM was used to measure several radial cross-section circles of a certain cylinder, as shown in Figure 1. According to the measurement requirements, suitable measuring needles and rods are selected. In this example, a measuring head with a diameter of 8mm, a measuring rod length of 114mm, a contact force of 150mN, and the normal direction of the measured section circle are consistent with the Z-direction of the CMM are used. Scan and detect several measuring points uniformly distributed on each measured cross-section (in this example, there are 3 measured cross-section circles, with 500 measuring points set on the circumference of each cross-section circle), fit the measured cylindrical surface using the minimum area method, and calculate the cylindricity. Repeat 3 measurements and take the average of the 3 measurements as the measurement result.

Figure 1. Schematic diagram of cylindricity measurement process based on CMM

3.2 Quantization of uncertainty components

The above analysis shows that the main components of uncertainty in CMM cylindricity measurement are uncertainty u1 introduced by CMM detection error, uncertainty u2 introduced by measurement repeatability, and uncertainty u2 introduced by measurement reproducibility. Below, we will analyze and calculate the quantification of each component.

The detection error of CMM can be directly referenced from the detection error MPEP in the CMM traceability certificate. However, according to JJF 1064-2010[7], it is known that the MPEP is calculated by coordinate ball detection. The tested object in this example is a cylindrical surface (with

3 axial cross-section circles), therefore, the roundness detection error of CMM is obtained using the traced standard coordinate sphere cross-section roundness. At the same position of the tested workpiece, fix the standard coordinate sphere in the same way, and use the same measurement strategy to repeat the measurement of the cross-section circle of the standard coordinate sphere three times. Calculate the detection error MPER of CMM roundness measurement is 0.30 μm. Assuming a uniform distribution, the standard uncertainty u(δ1) introduced by the CMM detection error is

$$u(\delta_1) = \sqrt{3} \times \frac{0.30\mu\text{m}}{\sqrt{3}} = 0.30\mu\text{m} \tag{4}$$

Under repetitive conditions, 10 independent measurements were taken on the cylindricity of the tested cylinder. According to the Bessel formula, the experimental standard deviation was calculated to be 0.08 μm. Due to the fact that the average of three measurements is taken as the measurement result during actual measurement, the standard uncertainty u(δ2) introduced by the repeatability of cylindricity measurement is

$$u(\delta_2) = \frac{0.08\mu\text{m}}{\sqrt{3}} = 0.05\mu\text{m} \tag{5}$$

Regarding the impact of measurement reproducibility on measurement results, considering that the CMM measurement program operates automatically, the cylindricity is a small error, and environmental temperature changes have little impact on it, this article sets the reproducibility difference measurement settings as changes in probe diameter, rod length, and measurement force, ignoring the influence of measurement personnel, measurement environment, and other factors. Three measurements were taken on the tested cylinder under each reproducibility condition, and the average of the three measurements was taken as the measured value under that condition, as shown in Table 1.

Table 1. Cylindricity measurement results under the conditions of reproducibility difference measurement setting

No.	Repeatability measurement settings (Measuring head diameter/measuring rod length/measuring force)	Measured value(μm)
1	8mm / 114mm / 150mN	1.58
2	8mm / 114mm / 100mN	1.33
3	8mm / 100mm / 150mN	1.29
4	8mm / 100mm / 100mN	1.57
5	5mm / 75mm / 150mN	1.51
6	5mm / 75mm / 100mN	1.52
7	5mm / 135mm / 150mN	1.43
8	5mm / 135mm / 100mN	1.52
9	3mm / 58mm / 150mN	1.35
10	3mm / 58mm / 100mN	1.47
11	3mm / 130mm / 150mN	1.55
12	3mm / 130mm / 100mN	1.54

According to the measurement results in Table 1, the uncertainty u3 introduced by the reproducibility of cylindricity measurement can be calculated using the Bessel formula as follows

$$u(\delta_3) = 0.10\mu\text{m} \tag{6}$$

3.3 Combined standard uncertainty

The composite standard uncertainty of cylindricity measurement based on coordinate measuring machine is calculated according to equation (3) as follows

$$u_c(r) = \sqrt{0.30^2 + 0.05^2 + 0.10^2}\mu\text{m} \approx 0.32\mu\text{m} \tag{7}$$

3.4 Expanded uncertainty

If the inclusion factor k is 2 is taken, the extended uncertainty of cylindricity measurement based on coordinate measuring machines is

$$U = ku_c(r) \approx 0.7\mu\text{m} \tag{8}$$

4. Conclusion

Based on the CMM based cylindricity measurement method, establish a black box evaluation model for the uncertainty of CMM cylindricity measurement, and analyze the sources of various uncertainties. Based on measurement examples, this paper elaborates on the evaluation process of cylindricity measurement uncertainty based on CMM, calculates the cylindrical extension uncertainty based on CMM, and provides reference for the evaluation of cylindricity measurement uncertainty in CMM.

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