Evaluation of Uncertainty in Linear Cylindrical Diameter Measurement based on Coordinate Measuring Machines

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Abstract. According to the measurement method of linear cylindrical diameter based on coordinate measuring machine (CMM), establish a black box evaluation model for the uncertainty of CMM linear cylindrical diameter measurement, and analyze the sources of each uncertainty. Combining measurement examples, this paper elaborates on the uncertainty evaluation process of linear cylindrical diameter measurement based on CMM, calculates the extended uncertainty of linear cylindrical diameter measurement based on CMM, and provides a reference for the uncertainty evaluation of linear cylindrical diameter measurement based on CMM.

Keywords: metrology; coordinate measuring machine; linear cylindrical diameter; uncertainty in measurement.

1. Introduction

Coordinate Measuring Machine (CMM) is an efficient and multifunctional precision geometric measurement instrument that can quickly and accurately measure the dimensions, shapes, positions, and other geometric quantities of components with complex shapes. Due to the diversity and complexity of CMM measurement objects, the evaluation of measurement uncertainty is relatively difficult. The main reason is that there are multiple sources of CMM measurement uncertainty, the construction of uncertainty models is complex, and the uncertainty components are difficult to accurately quantify. Generally speaking, when evaluating the uncertainty of CMM measurement, it is usually aimed at specific measurement tasks, which requires specific clarification of a certain measurement object, as well as relevant measurement environment elements, detection strategies, and other influencing conditions. To address the assessment of measurement uncertainty in CMM for specific tasks, relevant scholars have conducted research. Reference [2] studied the uncertainty evaluation method for CMM size measurement and established a black box model for measurement uncertainty evaluation. Using the method of measurement system analysis, quantitatively analyze the uncertainty components introduced by the six characteristic indicators of quantity values. Reference [3] adopts the measurement system analysis method to evaluate the uncertainty of coordinate measuring machines in product inspection based on quantity characteristic indicators. The national standard [4] GB/T 38762.1-2020 establishes a default set of standardized operations for linear dimensions, and specifies several specific standardized operation sets for linear dimensions facing cylindrical, spherical, toroidal, two relative parallel surfaces, and two relative parallel lines. 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 uncertainty evaluation of linear cylinder diameter measurement tasks based on CMM.

2. Measurement model

The diameter of a cylinder belongs to the global linear dimension in linear dimensions, and it is required that this dimension has a clear and specific specification operation set annotation [4]. The evaluation methods for cylinders include the minimum enclosing area method, least squares method, minimum circumscribed method, and maximum inscribed method [6]. When using CMM for linear cylinder diameter measurement, based on the representation of input and output of linear cylinder

diameter measurement, a black box modeling method based on quantity characteristic analysis is adopted to establish the following model

$$r = R + \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 \tag{1}$$

where, r is the linear cylindrical diameter measurement result, R is the estimated value of linear cylindrical diameter. δ1 is the impact of CMM dimension measurement indication error on measurement results. δ2 is the impact of the repeatability of linear cylindrical diameter measurement on the measurement results is represented by. δ3 is the impact of the reproducibility of linear cylindrical diameter measurement on the measurement results. δ4 is the effect of temperature changes on the diameter of a cylinder during measurement. δ5 is the effect of the difference in expansion coefficient between the tested cylindrical material and the CMM grating ruler. δ1 is a uniform distribution with an expected value of 0, and the standard deviation is the uncertainty u1 introduced by the CMM detection error. δ2 is a normal distribution with an expected value of 0, and the standard deviation is the uncertainty u2 introduced by measurement repeatability. δ3 is a normal distribution with an expected value of 0, and the standard deviation is the uncertainty u3 introduced by measurement reproducibility. δ4 is a uniform distribution with an expected value of 0, and the standard deviation is the uncertainty u4 introduced by the effect of temperature changes on the diameter of the cylinder during measurement. δ5 is a uniform distribution with an expected value of 0, and the standard deviation is the uncertainty u5 introduced by the difference in expansion coefficient between the measured cylindrical material and the CMM grating line.

According to the measurement model equation (1), ignoring the correlation between components, the formula for calculating the uncertainty of the composite standard is

$$u_c^2(r) = c_1^2 u^2(\delta_1) + c_2^2 u^2(\delta_2) + c_3^2 u^2(\delta_3) + c_4^2 u^2(\delta_4) + c_5^2 u^2(\delta_5) \tag{2}$$

where, c1 is 1, c2 is 1, c3 is 1 , c4 is 1, c5 is 1.

Then

$$u_c(r) = \sqrt{u^2(\delta_1) + u^2(\delta_2) + u^2(\delta_3) + u^2(\delta_4) + u^2(\delta_5)} \tag{3}$$

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 each cross-section circumference), fit the measured cylindrical surface with the least squares method, and calculate the fitted cylindrical diameter. Repeat 3 measurements and take the average of the 3 measurements as the measurement result.

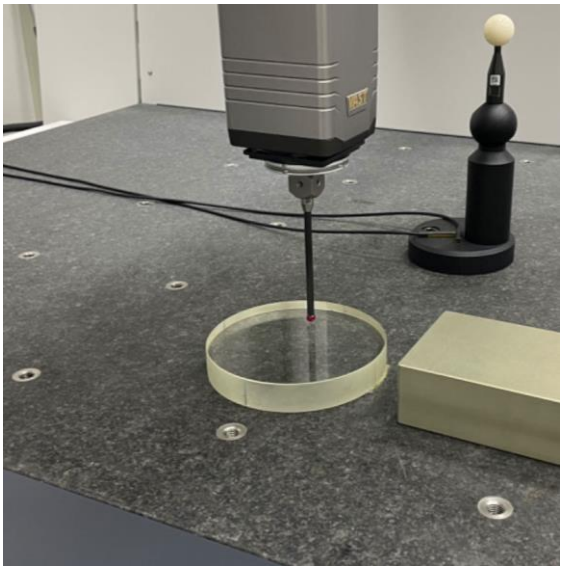


Figure 1. Schematic diagram of linear cylindrical diameter measurement process based on CMM

3.2 Quantization of uncertainty components

The above analysis shows that the main components of uncertainty in linear cylindrical diameter measurement based on CMM are uncertainty u1 introduced by CMM size measurement indication error, uncertainty u2 introduced by measurement repeatability, uncertainty u3 introduced by measurement reproducibility, uncertainty u4 introduced by the influence of temperature changes on cylindrical diameter during measurement, and uncertainty u5 introduced by the difference between the measured cylindrical material and the CMM grating linear expansion coefficient. Below, we will analyze and calculate the quantification of each component.

The CMM dimension measurement indication error can be directly referenced from the CMM traceability certificate. According to the traceability certificate, the MPE is ±(0.4μm+1.2×10-6L), where L is the dimension distance value. The nominal diameter of the cylinder in this example is 100mm. Assuming that MPE follows a uniform distribution, the standard uncertainty u(δ1) introduced by the CMM size measurement indication error is

$$u(\delta_1) = \frac{(0.4 + 1.2 \times 10^{-6} \times 100 \times 10^{3})\mu m}{\sqrt{3}} = 0.30\mu m \tag{4}$$

Under repeatability conditions, the linear cylindrical diameter of the measured plane is measured 10 times, and the standard deviation s of the repeated measurement experiment is calculated to be 0.05μm. The uncertainty u(δ2) introduced by the repeated measurement of the linear cylindrical diameter is

$$u(\delta_2) = \frac{0.28\mu m}{\sqrt{3}} = 0.16\mu m \tag{5}$$

Regarding the impact of measurement reproducibility on measurement results, considering that the CMM measurement program operates automatically, the linear cylindrical diameter 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. Measure the measured plane three times under each reproducibility condition, and take the average of the three measurements as the measured value under that condition. The measurement reproducibility results are detailed in Table 1.

Table 1. Linear cylindrical diameter measurement results under the conditions of reproducibility difference measurement setting

No.	Repeatability measurement settings (Measuring head diameter/measuring rod length/measuring force)	Measured value(mm)
1	8mm / 114mm / 150mN	100.0209
2	8mm / 114mm / 100mN	100.0214
3	8mm / 100mm / 150mN	100.0213
4	8mm / 100mm / 100mN	100.0211
5	5mm / 75mm / 150mN	100.0212
6	5mm / 75mm / 100mN	100.0212
7	5mm / 135mm / 150mN	100.0207
8	5mm / 135mm / 100mN	100.0205
9	3mm / 58mm / 150mN	100.0213
10	3mm / 58mm / 100mN	100.0211
11	3mm / 130mm / 150mN	100.0213
12	3mm / 130mm / 100mN	100.0212

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

$$u(\delta_3) = 0.28\mu m \tag{6}$$

When measuring, the coefficient of expansion of the cylindrical material is 11.5×10-6℃-1, and the temperature change during the measurement period is less than ±0.2℃. Assuming uniform distribution in this area, Class B method is used for evaluation. When the nominal diameter of a cylinder is 100mm, there are

$$u(\delta_4) = 0.2℃ \times 11.5 \times 10^{-6}℃^{-1} \times 100mm / \sqrt{3} \approx 0.13\mu m \tag{7}$$

The expansion coefficient of cylindrical material is 11.5×10-6℃-1, and the linear expansion coefficient of coordinate measuring machine glass grating is 0.1×10-6 ℃ -1. The range of environmental temperature change is less than 0.2℃. Assuming that the difference in linear expansion coefficient is uniformly distributed in this area, a B-class method is used for evaluation. When the nominal diameter of a cylinder is 100mm, there are

$$u(\delta_5) = 0.2℃ \times (11.5 + 0.1) \times 10^{-6}℃^{-1} \times 100mm / \sqrt{3} \approx 0.13\mu m \tag{8}$$

3.3 Combined standard uncertainty

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

$$u_c(r) = \sqrt{0.30^2 + 0.16^2 + 0.28^2 + 0.13^2 + 0.13^2}\mu m \approx 0.48\mu m \tag{9}$$

3.4 Expanded uncertainty

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

$$U = ku_c(r) \approx 1.0\mu m \tag{10}$$

4. Conclusion

According to the measurement method of linear cylindrical diameter based on CMM, establish a black box evaluation model for the uncertainty of CMM linear cylindrical diameter measurement, and analyze the sources of each uncertainty. Combining measurement examples, this paper elaborates on the uncertainty evaluation process of linear cylindrical diameter measurement based on CMM, calculates the expanded uncertainty of linear cylindrical diameter measurement based on CMM, and provides reference for the evaluation of uncertainty of linear cylindrical diameter measurement based on CMM.

References

[1] Zhang Guoxiong. Coordinate Measuring Machine. Tianjin University Press, 1999.

[2] Cheng Yinbao, Chen Xiaohuai, etc. Research on Uncertainty Estimation Model of CMM for Size Measurement, ACTA METROLOGICA SINICA, 2016, 37(5), 462-466.

[3] Chen Xiaohuai, Jiang Rui, etc. Measurement Uncertainty Analysis of CMM in Product Inspection and Conformance Testing, ACTA METROLOGICA SINICA, , 2017, 38(1), 51-55.

[4] Chinese standards. GB/T 38762.1-2020, Geometrical product specifications(GPS) -Dimensional tolerancing- Part 1: Linear sizes. Standards Press of China, 2020.

[5] Chinese standards. GB/T 24635.1-2020, Geometrical product specifications(GPS) – Coordinate measuring machines(CMM): Technique for determining the uncertainty of measurement – Part 1: Overview and metrological characteristics. Standards Press of China, 2020.

[6] Chinese standards. GB/T 1958-2017, Geometrical product specifications(GPS) - Geometrical tolerance - Verification. Standards Press of China, 2017.

[7] JJF 1064-2010 Calibration Specification for Coordinate Measuring Machine. China Metrology Press, 2010.