Evaluation of Uncertainty in Nonlinear Planar Distance Measurement based on Coordinate Measuring Machines

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

Keywords: metrology; coordinate measuring machine; nonlinear planar distance; 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 38762.2-2020 explains the uncertainty caused by applying dimensional specifications to control dimensions other than linear and angular dimensions, as well as the benefits of using geometric specifications to control these dimensions. Dimensional tolerances can be indicated using “±” tolerances or geometric specifications. The uncertainty caused by the use of ± tolerance for dimensions other than linear dimensions. The national standard [5] GB/T 24635-2020 provides technical guidelines for determining measurement uncertainty using CMM. On the basis of the aforementioned research, this article focuses on the uncertainty evaluation of nonlinear planar distance measurement tasks based on CMM.

2. Measurement model

The plane distance studied in this article belongs to nonlinear dimensions, which are not clearly labeled with specific standard operation sets [4]. Due to the fact that planar evaluation methods include minimum containment area method, least squares method, etc. [6]. Therefore, when evaluating the distance between planes, there is uncertainty, which needs to be taken into account when evaluating its measurement uncertainty. Using a black box modeling method based on quantitative characteristic analysis, establish the following model

$$d = D + \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 \quad (1)$$

where, d is the nonlinear planar distance measurement result, D is the estimated value of nonlinear planar distance. δ1 is the impact of CMM dimension measurement indication error on measurement results. δ2 is the impact of the repeatability of nonlinear planar distance measurement on the measurement results. δ3 is the impact of the reproducibility of nonlinear planar distance measurement on the measurement results. δ4 is the influence of the flatness of the measured plane on the plane distance. δ5 is the impact of changes in plane distance caused by different plane evaluation methods on measurement results. δ6 is the impact of temperature changes on the plane distance during measurement on the measurement results. 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 influence of the flatness of the measured plane on the plane distance. δ5 is a uniform distribution with an expected value of 0, and the standard deviation is the standard uncertainty u5 introduced by changes in plane distance caused by different plane evaluation methods. δ6 is a uniform distribution with an expected value of 0, and the standard deviation is the uncertainty u6 introduced by the impact of temperature changes on the plane distance during measurement.

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

$$u_c^2(d) = c_1^2 u^2(\delta_1) + c_2^2 u^2(\delta_2) + c_3^2 u^2(\delta_3) + c_4^2 u^2(\delta_4) + c_5^2 u^2(\delta_5) + c_6^2 u^2(\delta_6) \quad (2)$$

where, c1 is 1, c2 is 1, c3 is 1 , c4 is 1, c5 is 1 , c6 is 1.

Then

$$u_c(d) = \sqrt{u^2(\delta_1) + u^2(\delta_2) + u^2(\delta_3) + u^2(\delta_4) + u^2(\delta_5) + u^2(\delta_6)} \quad (3)$$

3. Evaluation of measurement uncertainty

3.1 Measurement example

Under laboratory environmental conditions, CMM was used to measure the distance between two planes of a certain part. The distance between the two planes belongs to nonlinear dimensions, with a nominal value of 320mm and a tolerance of ±0.01mm, 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, and a contact measuring force of 150mN are used. Conduct contact detection by uniformly distributing several measurement points on each measured plane (in this example, there are 2 measured planes, with 25 measurement points evenly distributed on each plane), fit the measured plane using the minimum area method, and calculate the distance between the centers of the two planes. Repeat 3 measurements and take the average of the 3 measurements as the measurement result.

Figure 1. Schematic diagram of nonlinear planar distance measurement process based on CMM

3.2 Quantization of uncertainty components

The above analysis shows that the uncertainty components of nonlinear planar distance measurement based on CMM mainly include uncertainty u1 introduced by CMM size indication error, uncertainty u2 introduced by measurement repeatability, uncertainty u3 introduced by measurement reproducibility, uncertainty u4 introduced by the flatness of the measured plane on planar distance, standard uncertainty u5 introduced by different planar evaluation methods on planar distance, and uncertainty u6 introduced by the influence of temperature changes on planar distance during measurement.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 ± (0.4) μm+1.2×10-6L), where L is the dimension distance value. The nominal diameter of the cylinder in this example is 320mm. Assuming that MPE follows a uniform distribution, the standard uncertainty u(δ1) introduced by the CMM size measurement indication error is

$$u(\delta_1) = 0.4\mu m + 1.2\times10^{-6} \times 320mm \times 10^3 \approx 0.78\mu m \tag{4}$$

Under repeatability conditions, the nonlinear planar distance of the measured plane is measured 10 times, and the standard deviation s of the repeated measurement experiment is calculated to be 0.56μm. The uncertainty u(δ2) introduced by the repeated measurement of the nonlinear planar distance is

$$u(\delta_2) = \frac{0.56\mu m}{\sqrt{3}} \approx 0.32\mu m \tag{5}$$

Regarding the impact of measurement reproducibility on measurement results, considering that the CMM measurement program operates automatically, the nonlinear planar distance 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. Nonlinear planar distance 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	321.2026
2	8mm / 114mm / 100mN	321.2010
3	8mm / 100mm / 150mN	321.2018
4	8mm / 100mm / 100mN	321.2018
5	5mm / 75mm / 150mN	321.2008
6	5mm / 75mm / 100mN	321.2012
7	5mm / 135mm / 150mN	321.2007
8	5mm / 135mm / 100mN	321.2021
9	3mm / 58mm / 150mN	321.2025
10	3mm / 58mm / 100mN	321.2024
11	3mm / 130mm / 150mN	321.2009
12	3mm / 130mm / 100mN	321.2023

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

$$u(\delta_3) = 0.73\mu\text{m} \tag{6}$$

The flatness of two planes was measured to be 0.5μm and 0.7 μm. The widths of the two planes are 280mm and 300mm respectively. Assuming that the influence of flatness follows a uniform distribution in this area, a B-class method is used for evaluation. There are

$$u(\delta_4) = \sqrt{0.5^2 + 0.7^2}\mu\text{m} \approx 0.86\mu\text{m} \tag{7}$$

The least squares method and the minimum area method were used to fit the measured plane, and the difference in plane distance between the two methods was calculated to be 1.1μ m. Assuming that the degree of influence follows a uniform distribution in the area, a B-class method is used for evaluation. There are

$$u(\delta_5) = \frac{1.1\mu\text{m}}{\sqrt{3}} \approx 0.64\mu\text{m} \tag{8}$$

When measuring, the expansion coefficient of the part 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, the B-class method is used for evaluation. When the plane distance is 320mm, there are

$$u(\delta_6) = 0.2℃ \times 11.5 \times 10^{-6}℃^{-1} \times 320\text{mm} / \sqrt{3} \approx 0.42\mu\text{m} \tag{9}$$

3.3 Combined standard uncertainty

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

$$u_c(d) = \sqrt{0.78^2 + 0.32^2 + 0.73^2 + 0.86^2 + 0.64^2 + 0.42^2} \approx 1.6\mu\text{m} \tag{10}$$

3.4 Expanded uncertainty

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

$$U = ku_c(d) \approx 3.2\mu\text{m} \tag{11}$$

4. Conclusion

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

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