Research and evaluation of the measurement uncertainty with the comparator

Chang’an Hu1,*, Jiangang Li2, Hongmei Ouyang3, Shutong Luo4, Fei Lv5, Dongyan Cai6
1236National Institute of Measurement and Testing Technology, Chenghua District, Chengdu, Sichuan, China
4Chengdu University of Technology, Chenghua District, Chengdu, Sichuan, China
5Chengdu Normal University, Wenjiang District, Chengdu, Sichuan, China
e-mail: jixie@nimtt.com

Abstract. As a kind of portable three-coordinate, the comparator is playing an more and more important role in precision industry measurement. Therefore, it is of great scientific significance and obvious socioeconomic benefits to carry out the research of comparator. This paper was based on rich experience with the institute in the field of the geometric measurement technology for a long time. And the measurement uncertainty of the instrument has been researched. The uncertainty of the diameter indication error is $U=1.2\mu m k=2$, the uncertainty of roundness indication error is $U=1.4\mu m k=2$, the uncertainty of sphere-center distance error is $U=1.5\mu m+7.2\times10^{-6}L k=2 L:m$, and the uncertainty of length indication error is $U=1.2\mu m+1.5\times10^{-6}L k=2 L:m$.

1. Introduction
With the transformation and upgrading of China's manufacturing industry into the fast lane, the current market for processing products of higher quality requirements, processing enterprises have brought efficiency and quality challenges. A new product, the comparator, has emerged. As an important precision measuring instrument, the comparator has been used more and more in high precision measurement. This paper has been engaged in the research of geometric measurement technology for a long time, and compared the measurement uncertainty of the diameter, roundness, sphericity distance and length error of the instrument with reference to relevant documents.

2. A comparison instrument
The comparator is a kind of geometric dimension measuring instrument, which is mainly composed of probe mechanism, control system, workbench and analysis software. It can through fast and accurate measurement, find out the nonconforming products, and realize the supervision and quality control of production. The working mode of the existing comparator can realize two kinds of automatic dot measurement and accurate scan measurement. The size of the measuring workpiece is less than 1m. The comparison instrument is shown in Figure 1.
3. Calibration Method

3.1. Error of diameter indication
Place the standard ball on the bench of the comparator and make the first measurement manually to determine the center and diameter of the circle, but do not record the measurement results. Automatic measurement is achieved through human-computer interaction. Each sphere should measure at least 5 points (it is recommended that at least 4 measurement points should be distributed on the equator line, one measurement point should be distributed on one pole of the sphere, and the distribution of other points should be evenly distributed according to the diameter of the sphere; Scan measurements can be made) to calculate the standard ball diameter. The standard ball was measured at least 5 times and averaged.

The difference between the average diameter and the standard diameter value is the diameter error:

\[ E_\phi = \bar{\phi} - \phi \]  

Type:

\[ E_\phi \]—— Diameter indication error, mm;
\[ \bar{\phi} \]—— The mean of the diameters, mm;
\[ \phi \]—— Diameter standard value, mm.

3.2. Roundness error
A tool ball is measured by means of a comparator, and all space point coordinates are fitted to the sphere by means of the least square method. The diameter of the sphere is the diameter of the tool ball being calibrated. The spherical center fitted by the above method is the center of two spheres. Among them, the maximum sphere is the smallest sphere that can contain all the space points in the sphere; The smallest sphere is the largest sphere contained by all the spatial points in the sphere. The difference between the maximum and minimum spherical radii is the roundness of the tool ball being calibrated. Calculate roundness and calculate the average value.

The difference between the average value of roundness and the standard value of roundness is the indicated error of roundness:

\[ E_R = \bar{R} - R \]  

Type:
3.3. Error of sphere-center distance indication
The carbon fiber ceramic ball plate was placed on the table of the comparison instrument, and the two balls were measured respectively according to the measurement steps of 6.4.1 to find the center position and calculate the center distance. The standard ball was measured at least 5 times and averaged.

The difference between the mean value of spherical-center distance and the standard value of spherical-center distance is the indicated error of spherical-center distance:

\[ E_D = \overline{D} - D \]  

Type:
\( E_D \) -- Error of spherical-center distance indication, mm;
\( \overline{D} \) -- The mean of the center of the sphere, mm;
\( D \) -- Standard value of spherical center distance, mm.

3.4. Length indication error
Fix the measuring block horizontally on the bench of the comparator and make the first measurement manually to determine the length and position of the measuring block. Automatic measurement is realized through human-computer interaction. The length of measurement block is calculated at least 5 times, and the average value is calculated.

The difference between the measured average and the standard value is the length indication error:

\[ E_L = \overline{L} - L \]  

Type:
\( E_L \) -- Length indication error, mm;
\( \overline{L} \) -- The mean value of length, mm;
\( L \) -- Standard value of measuring block length, mm.

4. Evaluation and analysis of measurement uncertainty

4.1. Evaluation of uncertainty of diameter indicated error
The main sources of uncertainty in the measurement process are: the uncertainty of the diameter of the standard ball, the uncertainty of the measurement repeatability, and the temperature automatic compensation of the measuring instrument, so the uncertainty of the relevant temperature can be ignored.

4.1.1. Uncertainty component of standard ball introduction
Uncertainty \( U = (0.2 + 0.5L) \mu m \), uniformly distributed, including factor \( k=2 \), the uncertainty component introduced by this item:

\[ u_1 = 0.1 \mu m \]

4.1.2. Measurement of uncertainty component introduced by repeatability
The diameter of the standard ball was repeatedly measured as follows: 0.0299962m, 0.029997m, 0.0299966m, 0.0299976m, 0.0299956m, 0.0299957m, 0.0299956m, 0.0299966m, 0.0299962m, 0.0299964m, 0.0299959m. According to the following formula, the experimental standard deviation of the measurement was 0.6 m, then the uncertainty component introduced:
4.1.3 Extended measurement uncertainty
The above standard uncertainty components are independent of each other. Therefore, the resultant uncertainty:

\[ u_c = \sqrt{u_1^2 + u_2^2} = 0.6 \mu m \]

The extended uncertainty was determined by including factor \( k=2 \), then \( U=1.2 \mu m \) \( k=2 \)

4.2. Evaluation of roundness error uncertainty
The main sources of uncertainty in the measurement process are: the uncertainty of standard ball roundness, the uncertainty of measurement repeatability, and the temperature automatic compensation of the measuring instrument. Therefore, the uncertainty of temperature can be ignored.

4.2.1. Uncertainty component introduced by standard ball
The uncertainty \( U=(0.02+0.05L) \mu m \) \( L: m \), uniformly distributed, including factor \( k=2 \). The uncertainty component introduced by this item:

\[ u_1=(0.01+0.025L) \mu m \]

\[ u_1=0.01 \mu m \]

4.2.2. Measurement of uncertainty component introduced by repeatability
Repeated measurements of the roundness of a standard ball are as follows: 1.05 \( \mu m \), 0.56 \( \mu m \), 0.78 \( \mu m \), 0.99 \( \mu m \), 0.82 \( \mu m \), 0.86 \( \mu m \), 0.62 \( \mu m \), 1.22\( \mu m \), 1.62\( \mu m \), 1.59\( \mu m \), 0.62\( \mu m \), 0.48\( \mu m \). The standard deviation of the measurement is 0.4 \( \mu m \), and the uncertainty component introduced is as follows:

\[ u_2 = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2} = 0.7 \mu m \]

Type:
\[ x_i \]--- diameter indication of the ith measurement, \( I=1,2,3... N, \mu m \);
\[ \bar{x} \]--- Arithmetic mean of the roundness indication for \( n \) measurements, in \( \mu m \);
\( n \)--- number of measurements.

4.2.3. Extended measurement uncertainty
The above standard uncertainty components are independent of each other. Therefore, the resultant uncertainty:

\[ u_c = \sqrt{u_1^2 + u_2^2} = 0.7 \mu m \]

Type:
\[ u_0 \]--- Measurement results Synthetic standard uncertainty, in \( \mu m \);
\[ u_1 \]--- Component of uncertainty introduced by standard sphericity in \( \mu m \);
\[ u_2 \]--- Measurement of uncertainty introduced by repeatability in \( \mu m \).
The extended uncertainty was determined by including factor \( k=2 \), then \( U=1.4 \mu m \) \( k=2 \)

4.3. Evaluation of uncertainty of error of sphere-center distance indication
The main sources of uncertainty in the measurement process are: the uncertainty of centroid distance of
carbon fiber ball plate, the uncertainty of measurement repeatability, and the uncertainty of temperature can be ignored since the measuring instrument has automatic temperature compensation.

4.3.1. Introduction of uncertainty component of carbon fiber pellets
The uncertainty \( U = (0.8 + L/600) \) μm, uniformly distributed, including factor \( k=2 \). The uncertainty component introduced by this item:

\[
u_1 = (0.4 + L/1200) \text{ μm}
\]

Where, \( L \) values are respectively: 15mm, 28mm, 44mm, 61mm, 89mm, 125mm, 242mm, and 320mm, so: \( u_1 = 0.4 \) μm.

4.3.2. Measurement of uncertainty component introduced by repeatability
The diameter of the standard ball was repeatedly measured, and the data were as follows: 175.9670mm, 175.9681m, 175.9691mm, 175.9695 mm, 175.9695 mm, 175.9697 mm, 175.9695 mm, 175.9695 mm. According to the following formula, the experimental standard deviation of the measurement was 2.2 μm, then the uncertainty component introduced by this item:

\[
u_2 = \sqrt{\frac{1}{n-1} \sum (x_i - \bar{x})^2} = 1.1 \mu \text{m}
\]

Type:
\( x_i \)-- diameter indication of the ith measurement, \( l=1,2,3... N \), μm;
\( \bar{x} \)-- Arithmetic mean of the roundness indication for \( n \) measurements, in μm;
\( n \)-- number of measurements.

4.3.3. Extended measurement uncertainty
The above standard uncertainty components are independent of each other. Therefore, the resultant uncertainty:

\[
u_c = \sqrt{u_1^2 + u_2^2} = 1.2 \mu \text{m}
\]

When the spheric center distance of 175mm is used for measurement, the inclusion factor \( k=2 \) is taken, then \( U = 2.4 \) μm \( k=2 \); When 320mm block is used for measurement, the inclusion factor \( k=2 \) is taken, then \( U = 3.0 \) μm \( k=2 \); When 61mm block is used for measurement, the inclusion factor \( k=2 \) is taken, then \( U = 1.8 \) μm \( k=2 \).

Extended measurement uncertainty, including factor \( k=2 \), then \( U = 1.5 \) m+7.2×10^{-6}L \( k=2 \) L:m

4.4. Evaluation of uncertainty of length indication error
The main sources of uncertainty in the measurement process are: measurement block length uncertainty, measurement repeatability uncertainty, the measurement instrument has automatic temperature compensation, so the uncertainty of related temperature can be ignored.

4.4.1. Uncertainty component is introduced into the gauge block
Uncertainty \( U_w = (0.10 + 1.0 \times 10^{-6}L) \) m L:m, uniformly distributed, including factor \( k=2.8 \), the uncertainty component introduced by this item:

\[
u_l = (0.04 + 3.6 \times 10^{-7}L) \text{ μm}
\]

Where, The maximum value of \( L \) is 500 mm, So: \( u_l = 0.04 \) μm.

4.4.2. Measurement of uncertainty component introduced by repeatability
To repeated measurement of the diameter of the standard ball, data is as follows: 125.0011 mm, 125.0009 mm, 125.0012 mm and 125.0003 mm, 125.0009 mm and 125.0011 mm, 125.0000 mm and 124.9999 mm, 124.9999 mm and 124.9997 mm, 124.9996 mm and 124.9995 mm, press type calculation, its measurement experiment standard deviation is 0.6 μm, is the introduction of the uncertainty
components:

\[ u_2 = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} = 0.6 \mu m \]

Type:
- \( x_i \) -- the length value of the ith measurement, \( i = 1,2,3...N, \mu m; \)
- \( \bar{x} \) -- Arithmetic mean value of length indication for n measurements, in \( \mu m; \)
- \( n \) -- number of measurements.

**4.4.3. Extended measurement uncertainty**

The above standard uncertainty components are independent of each other. Therefore, the resultant uncertainty:

\[ u_c = \sqrt{u_1^2 + u_2^2} = 0.6 \mu m \]

Type:
- \( u_1 \)--- Uncertainty component of measurement block length, in \( \mu m; \)
- \( u_2 \)--- Measurement of uncertainty introduced by repeatability in \( \mu m. \)

When 125mm measuring block is used for measurement, the inclusion factor \( k=2 \) is taken, then \( U=1.2 \mu m \)

When a 250mm measuring block is used for measurement, the factor \( k=2 \) is taken, then \( U=1.5 \mu m \)

Extended measurement uncertainty, including factor \( k=2 \), then \( U=1.2 \mu m + 1.5 \times 10^{-6} L \cdot \mu m \)

**5. Conclusions**

With the development of society, more and more precision equipment is used in the field of industrial measurement. At present, the application of comparator in the field of industrial measurement is increasing year by year. The evaluation of the measurement uncertainty of the equipment is helpful to analyze the measurement results.

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