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Article

Measurement Uncertainty Analysis of the Rotary-scan Method for the Measurable Dimension of Cylindrical Workpieces

Jiali Zhao[1,*], Liang Zhang[1], Dan Wu[1], Bobo Shen[1] and Qiaolin Li[2]

[1] School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou 730050, China

[2] Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China

[*] Corresponding author email: zhaojl@lut.edu.cn

Abstract: The measurement uncertainty analysis is carried out to investigate the measurable dimensions of cylindrical workpieces by the rotary-scan method in this paper. Due to the difficult alignment of the workpiece with a diameter of less than 3 mm by the rotary scan method, the measurement uncertainty of the cylindrical workpiece with a diameter of 3 mm and length of 50 mm which is measured by a roundness measuring machine, is evaluated according to GUM (Guide to the Expression of Uncertainty in Measurement) as an example. Since the uncertainty caused by the eccentricity of the measured workpiece is different with the dimension changing, the measurement uncertainty of cylindrical workpieces with other dimensions can be evaluated the same as the diameter of 3 mm but with different eccentricity. Measurement uncertainty caused by different eccentricities concerning the dimension of the measured cylindrical workpiece is set to simulate the evaluations. Compared to the target value of the measurement uncertainty of 0.1μm, the measurable dimensions of the cylindrical workpiece can be obtained. Experiments and analysis are presented to quantitatively evaluate the reliability of the rotary-scan method for the roundness measurement of cylindrical workpieces.

Keywords: measurement uncertainty; rotary-scan; cylindrical workpiece; various dimensions

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0 Introduction

With ongoing economic, scientific, and technological developments, the electronic devices used in daily lives are developing toward precision and miniaturization, and so the demand for high-precision manufacturing machinery is expanding[1]. Cylindrical rollers are important elements of bearings, and their machining accuracy and consistency affect the bearing quality[2]. Roundness is an important parameter for the cylindrical parts which is widely used in industries, such as the needle roller bears and RV reducer, in which the cylindrical parts are employed. The performance and life of this machinery are affected by the roundness of the cylindrical parts very much[3-4]. With recent developments in electronic, optical, and aerospace technology, the requirements imposed on the accuracy of workpiece surfaces are becoming more and more stringent[5]. Bad accuracy of the parts can cause friction. For controlling the quality of the cylindrical parts, precision measurement for the cylindrical parts is necessary[6-9]. Improving roundness measurement accuracy is critical to the development of future ultra-precision machining systems, especially in achieving higher accuracy and productivity[10]. Conventionally, the simple roundness measurement can be carried out by the two-point, three-point, and coordinate measuring machine[11-13]. In recent years, strong demands on precision roundness measurement can be found in many industrial fields due to the precision machinery such as the industrial robot and machine tool spindles. The ability to produce surfaces with such high precision is important for a variety of advanced technology applications[14]. Therefore, Precision roundness measurement methods are developed.

A multiple stylus method for the precision roundness measurement is proposed by Professor Gao at Tohoku University[15-16]. An improved multiple-problem method, in which spectra confocal displacement sensors are employed, is proposed by Doctor Bai at Tsinghua University[17]. An online roundness measurement method for a ball is proposed by Professor Cai at the Dalian University of Technology[18]. Conventionally, the precision roundness measurement can be performed by a roundness-measuring machine based on the rotary-scan method, such as the Talyrond 595H PRO[19]. However, not all cylindrical workpieces with various dimensions can be measured precisely by the rotary-scan method[20-22]. Measuring workpiece roundness using the rotary scanning method is influenced by many factors that need to be quantified[23]. Therefore, measurement uncertainty of the roundness measurement of cylindrical parts by the rotary scan method should be analyzed to investigate the reliability of the roundness-measuring machine.

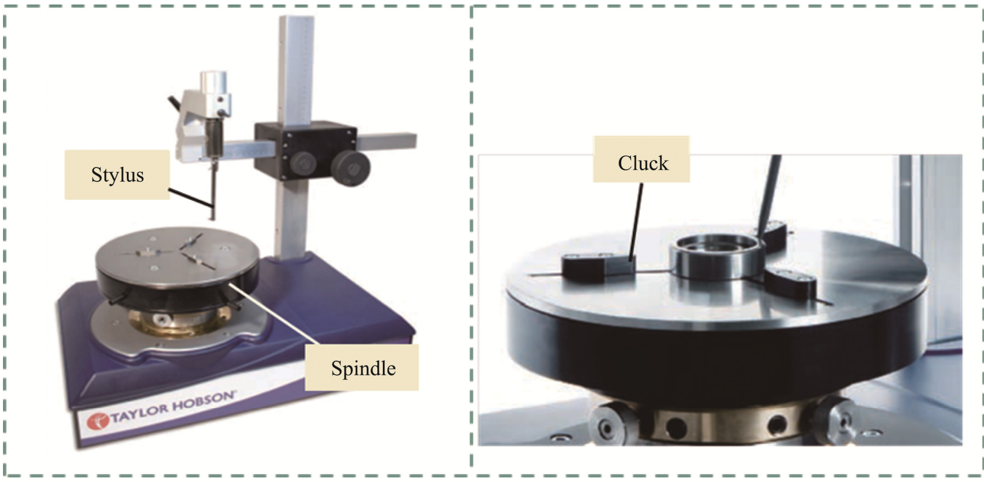
Conventionally, there is always a deviation(error) between the measurement results and the true value. Measurement error is composed of systematic and random errors. However, the definition of measurement error is based on the true value which cannot be obtained, meanwhile evaluation model is difficult to be established for the variation in repeated observations in most cases[24-26]. Therefore, the concept of measurement uncertainty for measurement error analysis is proposed in recent years. Uncertainty evaluation is a method for evaluating the reliability of measurement results and was published by seven international Organizations including ISO (International Organization for Standardization) in 1993[27-29]. Previously, measurement results were evaluated in terms of error (the difference between the measured and true values) and measurement variation, but there were problems with the difficulty of truly determining the true value and the lack of uniform evaluation methods of different research areas. To address this problem, uncertainty evaluation was established as a unified evaluation method that is not based on true value. The measurement uncertainty is necessary for multiple discipline, such as X-ray measurement, surface topography, radiometric, and energy harvesting etc[30-33]. In this paper, the uncertainty of the roundness measurement of cylindrical workpieces with various dimensions by a roundness measuring machine based on the rotary-scan method is evaluated for verifying the reliability of the machine. Experiments and analyses are carried out to demonstrate the measurement uncertainty.

1 Principle and Experiment

1.1 Principle

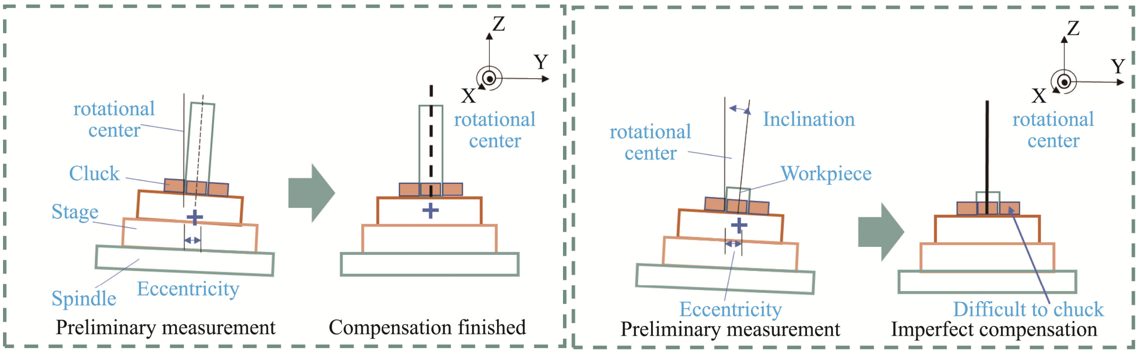
The conventional rotary scanning method is to mount the measured workpiece on a chuck and measure the circumference by scanning the cross-section of the workpiece mounted on the spindle with a probe by the roundness measuring machine as shown in Fig.1(a) and the centering chuck used to mount the workpiece as shown in Fig.1(b).

When measuring the roundness of cylindrical workpieces by rotary scanning method on a roundness measuring machine, due to the error of eccentricity and tilt easily occurring when mounting the workpiece, the roundness measuring machine makes preliminary measurements on two small cylindrical workpieces with different heights before the actual measurement to compensate the effect of eccentricity and tilt. When measuring a conventional workpiece, the measurement error can be reduced by analytical compensation, as shown in Fig.2(a). However, since the chuck of the roundness measuring machine has three jaws to hold the workpiece if the measured object is of small diameter, there is the problem of the limited range of motion of the jaws, so it is difficult for the chuck to mount the small diameter workpiece on the spindle, and even if the chuck can hold the small workpiece, the area that the stylus can scan will be reduced by the length of the workpiece stuck on the chuck, as shown in Fig.2(b).



(a) (b)

Fig.1 Photograph of roundness measuring machine
(a) Roundness measuring machine; (b) Centering chuck



(a) (b)

Fig.2 (a) Schematic of preliminary measurement of normal roll workpiece; (b) Schematic of preliminary measurement of small needle roller

1.2 Experiment

The measurement target is a small cylindrical part with a diameter of 3 mm and a length of 50 mm. Table 1 summarizes the specifications for small diameter roll pins of 3 mm (Eisen, 3.00 mm) in the instructions. The part to be measured was clamped in a three-jaw chuck and measured with a roundness measuring machine on two cross sections of 30 mm different heights to compensate for the eccentricity and tilt of the part. The workpiece is scanned with a roundness measuring machine stylus perpendicular to the workpiece surface to measure the shape of any cross section. The scanning speed of the stylus was set to 4 rpm and the same line was measured more than a dozen times, as shown in Fig.3(a).

2 Measurement Uncertainty Analysis of the Rotary-scan Method

3.1 Measurement Modeling

Firstly, an uncertainty evaluation was carried out for the measurement of the roundness of small cylindrical workpieces using the rotary scanning method with a roundness measuring machine. After organizing the measurement principles and methods, a mathematical model was constructed: the radial displacement $\Delta r(\theta)$ of the workpiece surface was read with a stylus scanning perpendicular to the workpiece surface as described in the experiments for the measurement of small 3 mm diameter cylinders. The roundness Δzq is expressed by the following equation (1), using a maximum $\Delta r(\theta)_{max}$ and a minimum $\Delta r(\theta)_{min}$ of the displacement.

$$\Delta z_q = \Delta r(\theta)_{max} - \Delta r(\theta)_{min} \tag{1}$$

As the radial displacement $\Delta r(\theta)$ is equal to the output of the roundness measuring machine stylus $\Delta m(\theta)$.

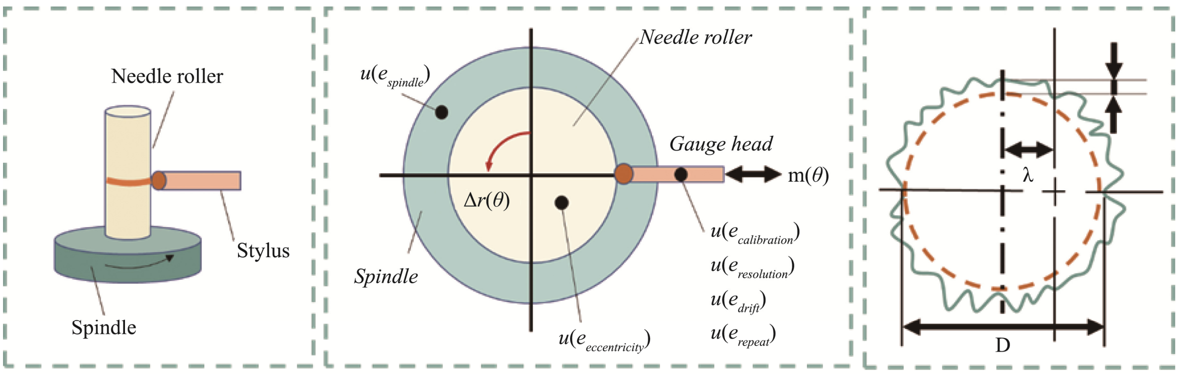
$$\Delta r(\theta) = \Delta m(\theta) \tag{2}$$

From equation (2), the combined deterministic criterion $u(\Delta r(\theta))$ for the radial dis-placement $\Delta r(\theta)$ at the surface of the workpiece can be expressed as follows:

$$u^2(\Delta r(\theta)) = \left(\frac{\partial \Delta r(\theta)}{\partial m(\theta)}\right)^2 u^2(m(\theta)) = u^2(m(\theta)) \tag{3}$$

Table 1 Specification of pin-gauge

Measurement points	Tolerance	Roundness	Cylindricity	Surface roughness
Centre	±0.5μm	0.3μm	0.15μm	0.05a



(a) (b) (c)

Fig.3 (a) Rotational scanning method for small cylinder roundness measurement; (b) Schematic of the measurement and the uncertainty components; (c) Schematic of the eccentricity of roll workpiece

The measurement uncertainty arises from the factors shown in Fig.3 (b). The uncertainty coefficients in the graph are:

$u(e_{calibration})$: Uncertainty in stylus calibration.

$u(e_{spindle})$: Uncertainty due to spindle rotation errors.

$u(e_{resolution})$: Uncertainty due to the resolution of the stylus.

$u(e_{drift})$: Uncertainty due to drift effects.

$u(e_{repeatt})$: Uncertainty in repeated measurements.

$u(e_{eccentricity})$: Uncertainty due to the eccentricity of the workpiece.

Taken together, the combined standard uncertainty of the final output of the stylus is given by:

$$u^2\left(m(\theta)\right) = u^2\left(e_{calibration}\right) + u^2\left(e_{spindle}\right) + u^2\left(e_{resolution}\right) + u^2\left(e_{drift}\right) + u^2\left(e_{repeat}\right) + u^2\left(e_{eccentricity}\right) \tag{4}$$

2.2 Measurement Uncertainty Evaluations

1. Evaluation of the standard uncertainty associated with each input value.

Once the uncertainties have been analyzed, the standard uncertainty for each uncertainty is derived using an appropriate evaluation method.

(1) Stylus calibration uncertainty $u(e_{calibration})$.

According to the calibration certificate provided by the roundness measuring machine for the calibration of the master ball, the uncertainty of the roundness of the master ball is 20nm (k=2). Therefore, the stylus calibration uncertainty is:

$$u\left(e_{calibration\_m}\right) = \frac{20}{2} = 10 \text{ nm} \tag{5}$$

The uncertainty in the repeated measurements of the calibrator is expressed as a standard deviation of 4.01nm (σ=1) for the 8 repeated measurements of the calibration, so the uncertainty in the repeated measurements during the calibration of the calibrated measuring machine is:

$$u(e_{calibration\_r}) = \frac{S}{\sqrt{n}} = \frac{4.01}{\sqrt{8}} = 1.42 \text{ nm} \tag{6}$$

The uncertainty of the stylus calibration can be calculated using a Type A evaluation with the following equation.

$$u\left(e_{calibration}\right) = \sqrt{u\left(e_{calibration\_m}\right)^2 + u\left(e_{calibration\_r}\right)^2} = \sqrt{10^2 + 1.42^2} = 12.02 \text{ nm} \tag{7}$$

(2) Uncertainty due to spindle rotation error $u(e_{spindle})$.

According to the specifications of the roundness measuring machine used for the measurement, the rotational error of the spindle in the radial direction is 0.01 + 6H/10000m (H: height from the table to the measurement point). In this experiment, the spindle rotation error was 37nm as the experiment was carried out at a height of H=45.0mm. The uncertainty due to the spindle rotation error is considered to be a rectangular distribution of ±37/2nm and can be calculated using the Type B evaluation method using the following equation.

$$u(e_{spindle}) \frac{e}{\sqrt{3}} = \frac{37/2}{\sqrt{3}} = 10.68 \text{ nm} \tag{8}$$

(3) Uncertainty due to stylus resolution $u(e_{resolution})$.

The resolution of the roundness measuring machine changes depending on the measuring magnification. The resolution was 1 nm since the measurement was performed at a magnification of 5000 times. Since the uncertainty due to probe resolution is considered to be a square distribution of ±0.5 nm, it is obtained by the following formula using B type evaluation.

$$u\left(e_{resolution}\right) = \frac{1/2}{\sqrt{3}} = 0.29 \text{ nm} \tag{9}$$

(4) Uncertainty due to drift effects $u(e_{drift})$.

The effects of temperature drift and thermal expansion due to temperature changes appear as steps from 0 to 360 in the output of the roundness measuring machine, directly affecting the amplitude parameter, and the value is around 10 nm to 25 nm. Assuming that the step due to drift is 25 nm, the uncertainty due to the influence of drift is considered to be a rectangular distribution of ±25/2 nm, so it is obtained by the following equation using B-type evaluation.

$$u\left(e_{drift}\right) = \frac{25/2}{\sqrt{3}} = 7.22 \text{ nm} \tag{10}$$

(5) Uncertainty of repeated measurements $u(e_{repeat})$.

The results of repeated measurements of the cross-sectional profile of a small cylindrical workpiece using a roundness measuring machine were used to estimate the uncertainty caused by the measurement error. Since it has a repeatability of 67.66 nm from the results of 10 repeated measurements, the uncertainty of repeated measurements can be obtained by the following formula using A type evaluation.

$$u\left(e_{repeat}\right) = \frac{67.66}{\sqrt{10}} = 21.40 \text{ nm} \tag{11}$$

(6) Uncertainty due to eccentricity of the workpiece $u(e_{eccentricity})$.

As shown in Fig. 3(c), when the probe scans the work surface, if there is eccentricity between the workpiece center and the spindle rotation center, an error will occur in the output reading, so it is necessary to consider the amount of error. The reading error S is expressed by the following formula using the displacement measurement magnification N, the workpiece eccentricity λ, and the workpiece diameter D:

$$S = N \times \frac{\lambda^2}{D} \tag{12}$$

When measuring a small needle with a diameter of 3 mm, preliminary measurements align the workpiece precisely. Therefore, if the eccentricity is λ = 0.01 μm and S = 1.67 nm, the uncertainty caused by the eccentricity of the workpiece is considered to be a rectangular distribution of ±1.67/2 nm, which can be determined by the B-type evaluation method according to the following equation.

$$u\left(e_{eccentricity}\right)=\frac{1.67/2}{\sqrt{3}}=0.48 \text{ nm} \tag{13}$$

2. Evaluation of the combined standard uncertainty

Table 2 summarizes the calculated results for each uncertainty. Based on these results, the combined standard uncertainty $u(m(\theta))$ of the stylus output can be expressed as follows.

$$u\left(m(\theta)\right)=\sqrt{\begin{array}{l}u^2\left(e_{calibration}\right)+u^2\left(e_{spindle}\right)+u^2\left(e_{resolution}\right)+\\ u^2\left(e_{drift}\right)+u^2\left(e_{repeat}\right)+u^2\left(e_{eccentricity}\right)\end{array}}$$

$$=\sqrt{12.02^2+10.68^2+0.29^2+7.22^2+21.40^2+0.48^2}$$

$$=27.73 \text{ nm} \tag{14}$$

Using the uncertainty calculated in equation (14), the combined standard uncertainty $u(\Delta r(\theta))$ is obtained from equation (2).

$$u\left(\Delta r\left(\theta\right)\right)=u\left(m\left(\theta\right)\right)=27.73 \text{ nm} \tag{15}$$

To simplify the problem, it is assumed that the maximum and minimum values of the displacements from the fitted circle are perfectly correlated. Therefore, the sum of the uncertainties of the maximum and minimum displacements from the fitted circle is expressed by the following equation.

$$u\left(\Delta z_q\right)=u\left(\Delta r\left(\theta\right)_{max}\right)+u\left(\Delta r\left(\theta\right)_{min}\right) \tag{16}$$

Assuming that the uncertainties of the sampling points are equal on the circumference, the following equation can be derived from equation (16).

$$u\left(\Delta z_q\right)=2u\left(\Delta r\left(\theta\right)\right) \tag{17}$$

Using the uncertainty calculated in equation (15), the combined standard uncertainty $u(\Delta zq)$ is obtained from equation (17) as follows.

$$u\left(\Delta z_q\right)=2u\left(\Delta r\left(\theta\right)\right)=2\times 27.73=55.46 \text{ nm} \tag{18}$$

Calculating the extended uncertainty for k=2 yields the following equation.

$$U\left(\Delta z_q\right)=ku\left(\Delta z_q\right)=2\times 55.46=110.92 \text{ nm} \tag{19}$$

From the above, the uncertainty in roundness measurement of a small cylindrical workpiece of 3 mm using a rotary scanning method roundness measuring machine is estimated to be ±107.68 nm, which is confirmed to be around the target measurement uncertainty of ±0.1μm. Table 3 summarizes the results of the standard uncertainty calculations to date.

2.3 Variation of Uncertainty Caused by the Change in Workpiece Diameter

The purpose of simulating the measurement uncertainty when the workpiece diameter varies is to investigate which cylindrical workpiece diameter is suitable for roundness measurement using a roundness measuring machine, which is a rotary scanning type measurement method. It is assumed that among the uncertainties (1) to (6) listed in the previous section, the uncertainty $u(e_{eccentricity})$ due to the eccentricity of the workpiece is the one that varies more with the diameter of the workpiece, while the others remain almost constant. Using equation (19), the graph of the variation of $u(e_{eccentricity})$ as the workpiece diameter varies from 0.01 mm to 50.00 mm is shown in Fig. 4 (a). The eccentricity of the workpiece is set to appear in a rectangular distribution with λ = 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 μm in each graph. When measuring an ordinary workpiece on a roundness measuring machine, the eccentricity can converge to about λ = 0.01, 0.02, 0.05 μm, because an algorithm can be applied in the computer to precisely correct the alignment during the initial measurement. However, when measuring small-diameter needles, i.e. cylindrical workpieces with short lengths and small

Table 2 Uncertainty budget of the output of stylus

Source of uncertainty	Symbol	Type	Coverage factor	Standard uncertainty	Sensitivity coefficient	$\lvert c_i\rvert\times u(x_i)$nm
Calibration of stylus	$u(e_{calibration})$	A	—	12.02	1	12.02
spindle error	$u(e_{spindle})$	B	$\sqrt{3}$	10.68	1	10.68
resolution	$u(e_{resolution})$	B	$\sqrt{3}$	0.29	1	0.29
Drift	$u(e_{drift})$	B	$\sqrt{3}$	7.22	1	7.22
Repeatability	$u(e_{repeat})$	A	—	21.40	1	24.40
eccentricity	$u(e_{eccrntricity})$	B	$\sqrt{3}$	0.48	1	0.48
combined standard uncertainty	$u(m(\theta))$			——		27.73

Table 3 Uncertainty budget of roundness measurement by roundness measuring machine

Source of uncertainty	Symbol	Type	Coverage factor	Standard uncertainty	Sensitivity coefficient	$\lvert c_i\rvert\times u(x_i)$nm
Calibration of stylus	$u(\Delta r(\theta))$	—	—	27.73	1	27.73
combined standard uncertainty	$u(\Delta z_q)$			——		55.46
expanded uncertainty(k=2)	$U(\Delta z_q)$			——		110.92

diameters, this algorithmic compensation is not fully applicable, and manual alignment is then required. Since the surface roughness of the workpiece is at least 0.1μm, the eccentricity for manual alignment is considered to be limited to λ = 0.1 0.2, 0.5μm. The eccentricity λ = 1, 2μm is a sufficiently feasible value, even for manual alignment. Fig. 4 (b) shows a zoomed-in view in the diameter range of 0.1 mm to 10 mm, where $u(e_{eccentricity})$ varies rapidly. At around 3 mm, where the computer algorithm becomes inapplicable, the magnitude of $u(e_{eccentricity})$ is around 100 nm even when the eccentricity is reduced to λ = 0.1μm in manual alignment, which is larger than the other uncertainty factors summarized in Table 2.

Substituting the previously calculated $u(e_{eccentricity})$ into the equation for the measurement uncertainty $u(\Delta zq)$ of the roundness measuring machine, the extended uncertainty calculated from this value is shown in Fig. 5 (a). The figure shows that even with manual alignment if the eccentricity can be reduced to λ = 0.1 μm, the target uncertainty of measurement can be about ±0.1μm for objects exceeding the workpiece diameter by about 10 mm. Fig. 5 (b) shows an extended plot over the diameter range of 0.1 mm to 10 mm, where $U(\Delta zq)$ varies rapidly. Below 3 mm, the computer algorithm is no longer applicable, and even when the eccentricity is reduced to λ = 0.1 μm in manual alignment, $U(\Delta zq)$ is still around 250 nm, which is about 2.5 times larger than the target measurement uncertainty. Therefore, if the workpiece diameter is smaller than 3 mm, the target uncertainty of about ±0.1 μm cannot be achieved unless the eccentricity is converged to λ= 0.01, 0.02 μm by using a preliminary measurement algorithm for alignment. however, in practice, precise alignment is not possible, so it is difficult to accurately measure the roundness of cylindrical workpieces smaller than about 3 mm using a roundness measuring machine.

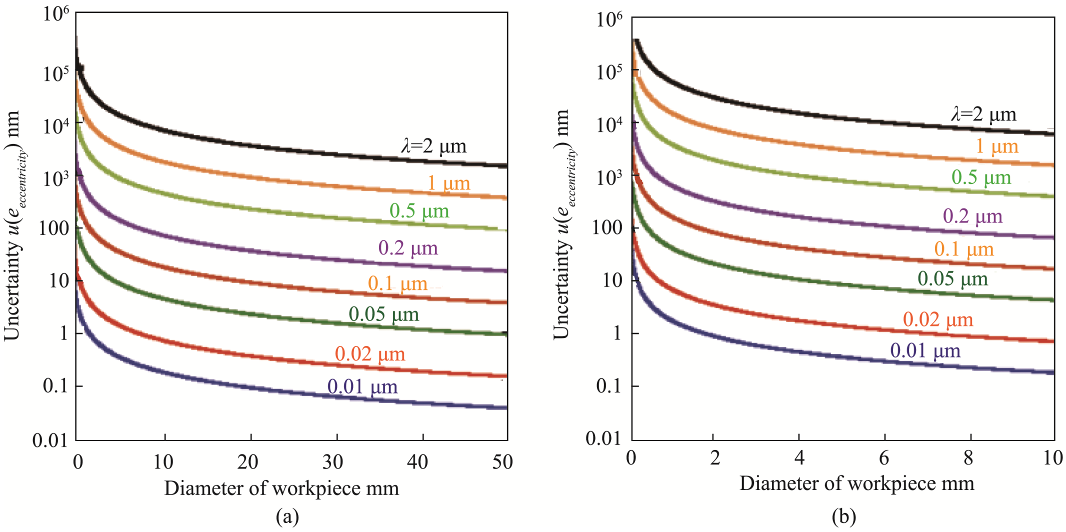


Fig.4 Variation of $u(e_{eccentricity})$ accordance with diameter of workpiece
(a) Diameter ϕ 0.01-50mm; (b) Diameter ϕ 0.01-10mm

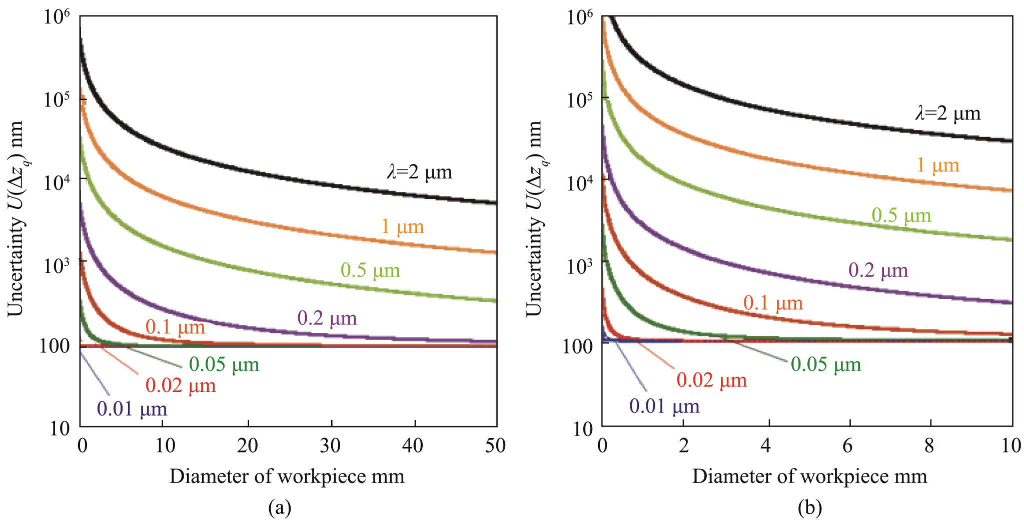


Fig.5 Variation of $U(\Delta z_q)$ in accordance with the diameter of the workpiece
(a) Diameter ϕ 0.01-50mm; (b) Diameter ϕ 0.01-10mm

3 Conclusion

To quantitatively verify the reliability of the rotary scan method for the measurement of cylindrical workpieces, uncertainties are evaluated. The expanded uncertainty of the roundness measurement of the cylindrical workpiece with a diameter of 3 mm and length of 50 mm using the rotary scan method on a roundness measuring machine was evaluated to be ±107.68 nm, which was confirmed to be around the target measurement uncertainty of ±0.1μm. To investigate the measurable workpiece diameter and alignment conditions, the change in measurement uncertainty for the rotary-scan method is simulated when the workpiece diameter was changed. Since the eccentricity is changing with the workpiece dimension changing, the analyses of all the components of the uncertainty for the cylindrical workpieces with different are the same except for the uncertainty caused by eccentricity. Thus, the diameters of the workpiece are set to be a variation from 0.01 to 50 mm, and the eccentricities of these cylindrical workpieces are set to be a variation of 0.01, 0.02, 0.05, 0.1 0.2, 0.5, 1, 2 μm respectively, which is a rectangular distribution. Although the alignment can be achieved by the software automatically, manual alignment is necessary when the length of the cylindrical workpiece becomes short. However, when the diameter of the measured workpiece is less than 3 mm, manual alignment cannot reach the correct eccentricity. Therefore, it is not possible to achieve a roundness measurement uncertainty close to the target value of the measurement uncertainty of 0.1μm when the dimension of the cylindrical workpiece becomes smaller. Therefore, in the field of high requirements for measurement accuracy and when the measured workpiece is smaller than 3mm, the traditional measurement method is no longer applicable.

Author Contributions:

Zhao Jiali: Conceptualization (lead); Writing - original draft (lead); Methodology (equal); Resources (lead). Zhang Liang: Writing – review & editing (lead); Formal analysis (lead); Investigation(equal); Data curation(equal); Writing – review & editing (equal). Wu Dan: Writing – review & editing (supporting). Shen Bobo: Investigation(equal). Li Qiaolin: Writing – review & editing (supporting).

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Data Availability:

The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary Information files.

Conflict of Interest:

The authors declare no competing interests.

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