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ROUNDNESS MEASUREMENT AND ITS UNCERTAINTY IN AN INTERNATIONAL COMPARISON

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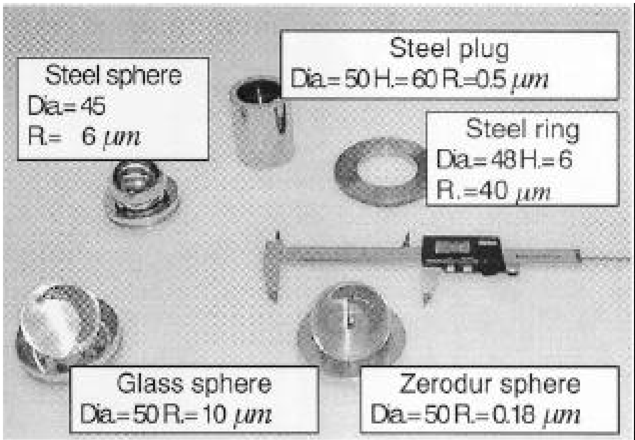
Abstract: A highly accurate roundness measuring instrument and the calibration system of its probe were developed. The international round robin comparison of form measurement organized by the CIRP was carried out from 1996 to 1998. The measuring results obtained by using this instrument and system correspond satisfactory to the results by PTB with very small measurement uncertainty. For example, the obtained roundness of zerodur sphere with 50 mm diameter is about 179 nm with 9 nm (k=2) in uncertainty of measurement, while the corresponding result by PTB is 184nm and 10nm respectively.
Keywords: CIRP, round robin comparison, roundness, measurement uncertainty

1 INTRODUCTION

In recent industry, it becomes in high demand to improve rotary movement in both speed and accuracy in order to achieve machining with high accuracy, high efficiency, low vibration, and low noise. Accordingly, it becomes much more important for products to measure and to control roundness profiles of rotary motion components with high accuracy, such as axle or shaft, bearing, and so on.

We have been supplying roundness measuring instruments to industry in worldwide since the beginning of 1970's. Also, we have constantly been trying to improve the accuracy of roundness measuring instruments and the probe calibration. As a recent achievement, we have developed the roundness measuring instrument and the probe calibration system to achieve nanometer order in repeatability by means of analyzing each uncertainty factor related to roundness measurement and of assigning target for each permissible uncertainty.

Meanwhile, there had not been realized international comparison of form measurement performance and reliability in spite of its importance in precision engineering. For these reasons, „The international round robin comparison of form measurement„ was planned by CIRP (International Institution for Production Engineering Research), and carried out from 1996 to 1998 [1]. Five artifacts in the round robin comparison are shown in Figure 1. Total nine of roundness measurements were specified on the instruction, that is, the equator of glass sphere, steel sphere, and zerodur sphere, the middle and near both sides of plug and ring respectively. In each case, 4 type of roundness measurement and its uncertainty were specified, that is, 2 kinds of filters (50upr and 500upr) and 2 kinds of roundness evaluation method (LSC: Least Squares Center method and MZC: Minimum Zone Center method). In short, total 36 roundness measurement tasks were instructed. Additionally, another 12 measurement tasks were instructed in case of plug and ring, that is, straightness of 4 generating line and 2 couples of parallelism



note: Dia.= diameter, H.=Hight, R.= Roundness deviation

Figure 1. Five artifacts in the round robin comparison.

in each. After all, total 48 measurement tasks and its uncertainty report were specified [2].

Our company also approved in the purpose of the round robin comparison and participated by using our developed roundness measuring instrument and probe calibration system. We measured the artifacts received in November 1997 for given one month with careful consideration of measurement environment and the setting of the artifacts and the probe. Our measurement results correspond satisfactory to the results by PTB (Physikalisch-Technische Bundesanstalt, Germany), who is the pilot laboratory of the round robin comparison, with very small measurement uncertainty [1], [3].

This paper explains the outline of our developed high-precision roundness measuring instrument and probe calibration system first, the estimation of measurement uncertainty and the measurement procedure second, and the results of round robin roundness measurements last.

2 SUMMARY OF OUR INSTRUMENT AND CALIBRATION SYSTEM

The appearance of our developed instrument is shown in Figure 2. The development was proceeded to reduce dispersion and deviation of the measurement. Table 1 shows main dispersion factors of the developed instrument, means of improvement, and the specifications. Target value of total dispersion except for the calibration system, probe characteristics, and artifact setting was set s_S=1.1 nm, and each dispersion was assigned as follows; s_{SM}=0.83 nm, s_{PS}=0.55 nm and s_E=0.45 nm.

As the result, the good repeatability was obtained as showing in Figure 3. Moreover the results of each dispersion are shown in Table 3 later. s_{SM} and s_E on Table 1 are included in u3 on Table 3, s_{PS} on Table 1 corresponds to u5 on Table 3. The total repeatability shows the approximate level of the intercomparison in Europe [4] prior to the present round robin comparison.

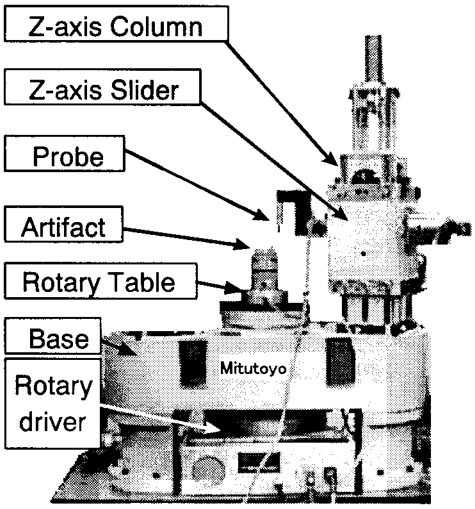


Figure 2. Appearance of developed roundness measuring instrument

Table 1. Main dispersion factors, means of improvement and specifications of the developed instrument.

Symbol	Factor	Means of improvement and specifications
s_{SM}	Vibration caused by measuring motion	1) Rigid and thermally symmetrical structure 2) High stiffness axle and thrust air bearing for rotary table 3) Built-in direct drive AC motor with high resolution rotary encoder (1 / 10000 degree) 4) High precise AC motor control technology (velocity ripple: less than 0.033 %) 5) Measuring rotation speed: 6 min^{-1} 6) Data sampling pitch: 36000 points / Revolution
s_{PS}	Elastic deformation, Electrical signal noise	1) Reducing friction 2) Averaging and filtering of signal 3) Filter: 2RC digital, phase correct, 75% transmission 4) Diameter of the stylus: 1.6 mm Material of the stylus: Tungsten carbide Applied contacting force: 3 mN
s_E	Instability of temperature, Vibration	1) Air control and thermal insulating cover (thermal fluctuation: less than 35 mK / 1 hour) 2) Ambient temperature: 20.00 °C ~ 20.26 °C (during the all measurements) 3) Disturbance vibration acceleration: less than $1x10^{-5}$ m/s^2 (1 m Gal) (Using floating base)

Main factors of deviation are the spindle rotation error of the rotary table and characteristics of the probe. The former factor, that is the radial error component by the rotary table, is corrected by multi-step method.

The characteristics of probe is compensated by subtracting the deviation obtained through the calibration system as shown in Figure 4 [5]. This system consists of the laser interferometer, which has 0.3nm resolution and 1.1 x 10^{-9} wavelength stability, and the scanning mechanism to displace the probe by scanning the mirror in optical axis direction. These components are placed in the thermal insulation bench installed on the vibration isolation system. Temperature, humidity, atmospheric pressure and CO_2 density in the bench are monitored by calibrated instruments. The laser wavelength is defined by the refractive index of air compensated with these monitored value. In Figure 4, Ld means dead pass. The dead pass needs to be shortened as much as possible to minimize system uncertainty. In this system, the dead pass is set at the shortest possible limit Ld=42.7 mm under the mechanical system configuration. L means measuring stroke of the probe, that is less than 400.

Table 2 is the uncertainty budged sheet for the probe calibration system. In this calibration system, the combined standard uncertainty is uc(1)=1.03nm. The combined standard uncertainty is actually defined by refractive index fluctuation u(21). This uc(1) value corresponds to u1 in Table 3 mentioned in the latter.

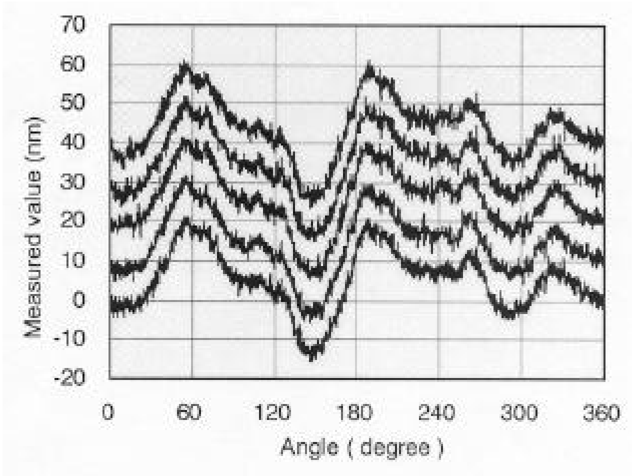


Figure 3. Repeatability of the developed instrument. Each graph is shifted for visual comparison.

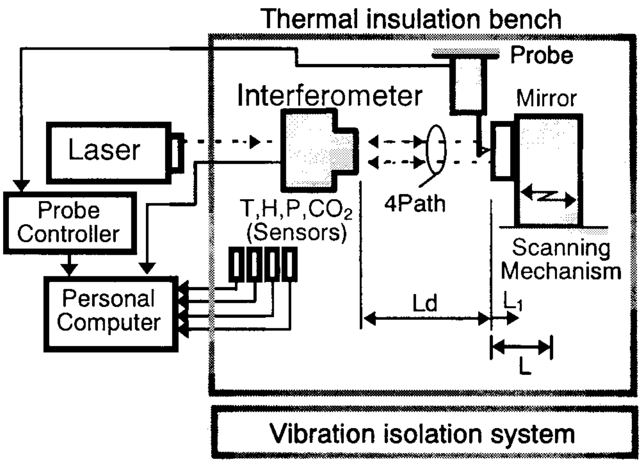


Figure 4. Block diagram of the probe calibration system,
Ld: dead pass,
L: measurement length

Table 2. Uncertainty budged sheet for the probe calibration system.

Uncertainty factor	Symbol	Uncertainty in calibration result nm
1. Laser wave length 1) Uncertainty of calibration 2) Temperature dependency	u(1) u(11) u(12)	rms1 = 0.5 x 10^{-8} x L 0.5 x 10^{-8} x L 3.9 x 10^{-10} x L
2. Compensation in refractive index of air 1) Fluctuation at refractive index of air 2) Uncertainty of each environment measurement instruments	u(2) u(21) u(22)	rms2=1.03 rms21=1.03 rms22=7.8 x 10^{-8} x L
3. Calibration device 1) Resolution of device 2) Abbe error 3) Cosine error	u(3) u(31) u(32) u(33)	rms3=0.087 0.3 x 0.29 (HP10897B H.R.) 0 (HP10716A) 0 (HP10716A)
Combined standard uncertainty	uc(1)	1.03

3 ESTIMATION OF THE UNCERTAINTY OF THE MEASUREMENT

Referring to the zerodur sphere of roundness deviation about 179 nm on condition of roundness evaluation method LSC and filter 500 upr (undulation per revolution), the estimation of uncertainty and uncertainty factors are considered as follows:

3.1 The probe calibration system (u1)

u1=1.03 nm is the aforementioned combined standard uncertainty of the probe calibration system.

3.2 Characteristic of probe (u2)

u2 is uncertainty of the probe characteristic after calibration.

Figure 5 shows a result of measurement by the probe calibration system. In order to reduce error induced by air-turbulence, each data at 20 measurement points in reciprocation within the measuring stroke is averaged from 2,000 times data sampling.

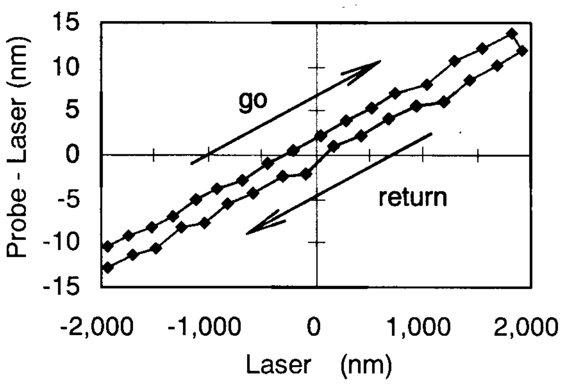


Figure 5. A result of measurement by the probe calibration system.

u2 consists of the following 5 factors: dispersion of 2,000 times data sampling u21=2.09 nm, regression line gradient uncertainty by the probe non-linearity u22=0.60 nm, uncertainty by residuals, etc. u23=1.67 nm, and the calibration value difference between before and after the round robin measurement u24=0.55 nm. In measurement, thrust force at the right angle to displacement direction acts on stylus of the probe. The uncertainty by the force u25=1.64 nm is estimated from the repeatability in measurement of a standard hemisphere. By combination of these, u2=3.24 nm is obtained.

3.3 Spindle rotation error through one month (u3)

u3 is uncertainty of the spindle rotation error including environmental fluctuation through given one month. As aforementioned, the measurement data of each artifacts are compensated by subtracting the spindle rotation error obtained through multi-step method. In the multi-step method, data is sampled in 15 degree pitch (360 degree / 24 step) by using our own made standard hemisphere certified by PTB with 6 nm (MZC500). In multi-step method, the roundness profile components of the integer multiple undulation per revolution number of the multi-step method step (24) becomes the uncertainty because these components can not be calculated. In order to evaluate this uncertainty, the components of integer multiple of the 24 upr are extracted from measured data of the standard hemisphere, and the roundness deviation by this component is calculated.

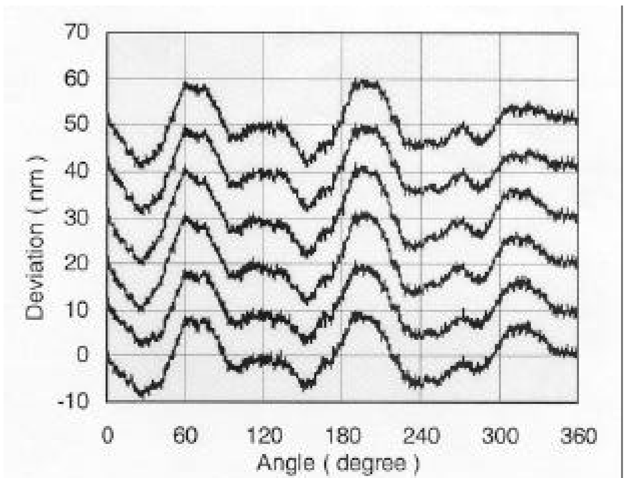


Figure 6. The spindle repeatability through one month. Each graph is shifted for visual comparison.

The uncertainty of multi- step method u31=0.73 nm is the roundness deviation by these components. Moreover, observation data by multi- step method is collected several times during our period given in the round robin measurement. The uncertainty of repeatability in multi-step method u32=1.03 nm and the uncertainty of spindle rotation error of the measuring instrument u33=1.23 nm is obtained from the collected data. Influence by height to the spindle rotation error is eliminated by means of multi-step method operated at the height where the artifact is measured for every each artifact. By combination of these, u3=1.76 nm is obtained. Figure 6 shows an example of result related to u33.

3.4 Setting of the artifact and the probe (u4)

u4 is overall uncertainty of day different repetitive measurement considering changes of artifact and probe setting. u4 also includes roundness uncertainty based on dispersion of the measurement position. Total 40 data are obtained by 10 measurements a day in 4 different days.

As for setting the artifact, out of centering between the artifact and the rotating axis of the measuring instrument is aligned less than 1, and parallelism between north-pole axis of the artifact and the rotating axis of the measuring instrument less than 1 / 20 mm respectively.

Figure 7 shows how to determine equator height. As the instruction specifies to measure on the equator in case of spheres, the stylus needs to be positioned on the equator height. The equator height coordinate is determined as the peak point of the probe displacement–height curve shown on Figure 7, which can be detected by scanning probe around the equator height. In this method, the standard deviation of positioning the stylus on equator is 8.4. Also in case of roundness and straightness measurement of the plug and the ring, the appropriate mean to determine each measurement start point is contrived.

As the result of this consideration, standard deviation u4=1.69 nm of 40 measured values is obtained in case of the zerodur sphere (LSC500). A record of roundness profile of the zerodur sphere is shown in Figure 8.

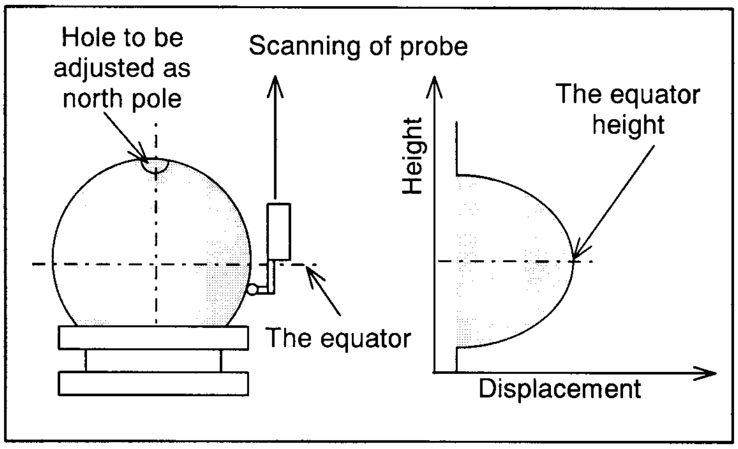


Figure 7. Equator height determination.

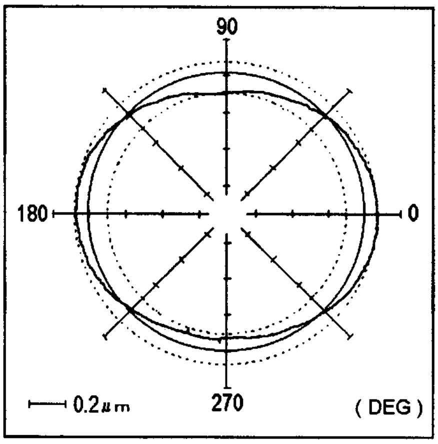


Figure 8. A record of roundness profile of zerodur sphere. (LSC, 500 upr)

3.5 Probe signal processing (u5)

u5 is uncertainty of the probe output signal processing for noise suppression. In addition to hardware contrivance to suppress noise, averaging process is applied to data acquisitions. As the result, uncertainty of the probe signal processing u5=0.49 nm is obtained on condition of rotation speed 6min^{-1} and filter 500upr.

3.6 Summary of measurement uncertainty

Table 3 shows the value of uncertainty factors u1, u2, u3, u4, and u5 mentioned above and the combined standard uncertainty. The expanded uncertainty is estimated at 9 nm (k=2).

Table 3. The uncertainty factors and combined standard uncertainty in measuring the zerodur sphere with diameter of 50 mm and roundness deviation about 179 nm (LSC500).

Symbol	Factor of uncertainty	Type	Standard uncertainty
u1	Probe calibration system	A,B	1.03 nm
u2	Characteristics of the probe	A,B	3.24 nm
u3	Spindle rotation error through one month	A	1.76 nm
u4	Setting of the artifact and the probe	A	1.69 nm
u5	Probe signal processing	A	0.49 nm
		Combined standard uncertainty	4.2 nm
		Expanded uncertainty (k=2)	9 nm

4 RESULT OF THE ROUND ROBIN MEASUREMENT

In the round robin measurement, 22 organizations from Europe, North America, and Asia agreed to participate. 19 participants, that is 3 industrial enterprises, 9 universities, and 7 national metrology institutes, have sent results. However, only a few participants including our company managed to complete every 48 of measurement tasks on all 5 artifacts given by the Instruction [1].

Table 4 shows the roundness measurement results and the uncertainty on condition of filter 500 upr and roundness evaluation method LSC by us and PTB [3]. As the En number [6] is less than 1 in every measurement tasks, both measured values of us and PTB correspond satisfactory.

Table 4. The comparison of our roundness deviation with the result of PTB in the CIRP-Form measurement intercomparison. (some LSC500 examples) unit: µm

Participants	Task	Zerodur	Plug (middle)	Steel	Glass	Ring (middle)
Mitutoyo	Roundness deviation	0.179	0.402	6.29	10.42	46.9
	Uncertainty	0.009	0.016	0.03	0.07	0.2
PTB	Roundness deviation	0.184	0.4	6.28	10.485	46.9795
	Uncertainty	0.01	0.1	0.225	0.1	0.25
Difference of roundness deviation		-0.005	0.002	0.01	-0.065	-0.0795
En number		0.37	0.02	0.04	0.53	0.25

Above correspondence shows that appropriately of uncertainty estimation and superiority of the roundness measuring instrument and the calibration system.

5 CONCLUSION

Our company has continuously been pursuing the higher precision in roundness measurement. As an achievement, the roundness measuring instrument and the calibration system with repeatability in nanometer order was developed. By using the developed measuring instrument and calibration system, we participated in the international round robin comparison organized by CIRP and achieved the following results:

1) For every measurement tasks we reported the results. Comparing the results with the value by PTB, En number is well under 1 on almost all measurement tasks.
2) In our developed roundness measuring instrument and probe calibration system, we summarize and estimate the uncertainty factors in regard of the round robin measurement into five main factors. This paper shows the instance related to roundness deviation of the five artifacts.
3) In case of measuring the zerodur sphere with diameter of 50 mm and roundness deviation about 179 nm (LSC500), difference of roundness deviation between our result and the result by PTB is 5 nm and the expanded uncertainty correspond approximately.

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