CALIBRATION AND UNCERTAINTY EVALUATION OF FLICK STANDARD USING COORDINATE-MEASURING MACHINE

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Abstract:

Flick standard is a cylindrical artifact with a flat part for calibrating the magnification of a probe of roundness measuring-instruments. A probe magnification of roundness measuring-instruments is evaluated by measuring a calibrated flick value of a flick standard. The flick value is a distance between a cross-section circle and a cross-section line. In factory field, it is required that the flick value is calibrated within 0.1 μm with respect to several micrometer to several hundred micrometer. The flick value is generally calibrated by an accurate roundness measuring-instrument. It has a linear error of a probe with about 0.1% or more gain error. When the flick value is 100 μm, the measurement uncertainty is 0.1 μm or more. We calibrated a flick standard using an ultra-high accurate coordinate measuring-instrument (CMM) with a laser interferometer to ensure the measurement uncertainty within 0.1 μm. The length measurement system by the laser interferometer is according to the abbe principle. In this paper, we describe the calibration method of a flick standard using the CMM. We calibrated the flick standard using a multiple-measurement technique to eliminate the systematic error of the CMM and estimated its uncertainty based on the analysis of variance. Finally, the proposed calibration method is validated through experiments.

Keywords: Flick standard, Roundness measuring-instrument, Coordinate measuring-machine, Interferometer, Uncertainty

1. INTRODUCTION

The flick standard is a cylindrical artifact for calibrating a probe of roundness-measuring instruments[1]. The roundness measuring-instruments measure a flick value of a flick standard. The magnification of probe is calibrated by comparing its dynamic displacement with the calibrated flick value. The National Metrology Institute of Japan (NMIJ) has been started the calibration service of the flick standard in June 2014.

Figure 1 shows the cross-sectional view of a flick standard. O and r_c are a center point and radius calculated by the least square circle with respect to the circular part of a flick standard without a flat part, respectively. d is a perpendicular distance from the center O to the line calculated by the least square line with the flat part. We defined the flick value by

$$h = r_c - d. \tag{1}$$

The angle θ_f between both ends of flat part and O is calculated by

$$\theta_f \approx \sqrt{\frac{8h}{r_c}}. \tag{2}$$

We defined the calculation range which was the circular part with $1.2 \times \theta_f$ and the linear part with $0.8 \times \theta_f$.

The flick value is generally calibrated by an accurate roundness measuring-instrument[2]. It has a linear error of a probe with about 0.1% or more gain error. When the flick value is 100 μm, the measurement uncertainty is 0.1 μm or more. In factory field, it is required that the flick value is calibrated within 0.1 μm with respect to several micrometer to several hundred micrometer. We calibrated a flick standard using an ultra-high accurate coordinate measuring-instrument (CMM) with a laser interferometer to ensure the measurement uncertainty within 0.1 μm. The length measurement system by the laser interferometer is according to the abbe principle. In this paper, we describe the calibration method of a flick standard using the CMM.
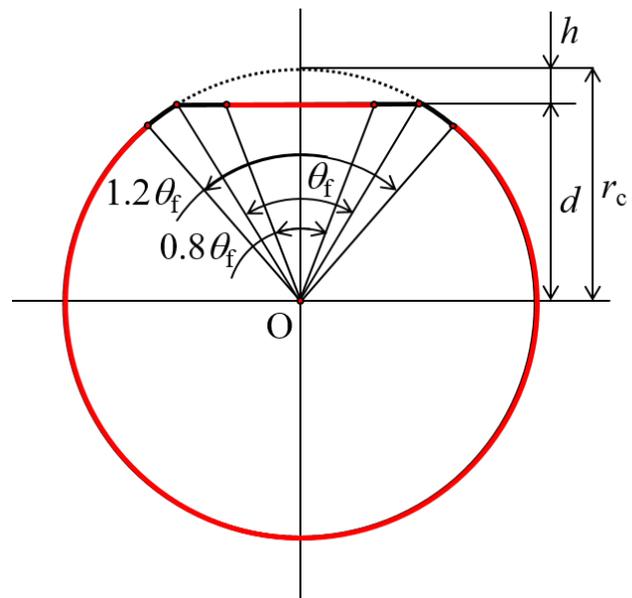

Fig. 1: Cross-sectional view of a flick standard

2. MEASUREMENT SYSTEM OF COORDINATE MEASURING-MACHNIHE

We calibrated a flick standard using an ultra-high accurate coordinate measuring-machine (Panasonic, UA3P-L). Figure 2 and 3 show a systematic view and a photograph of the CMM, respectively. The CMM is composed of a probe system and air slide of three orthogonal axes. The flick standard was placed in the XY air slide table. The moving distances of X, Y, Z1 and Z2 axis are measured by a laser interferometer. The Z1 moving distance is the Z displacement of XY stage. The Z2 moving distance is the Z displacement of the probe system. The optical system is designed such that optical axes pass through the probe center, is in accordance with the Abbe principle. The flick standard is scanned by moving the XY stage with a feedback control which the inclination of the probe is constant regardless of the flick value. The flick value is calculated by the measured stage displacements.
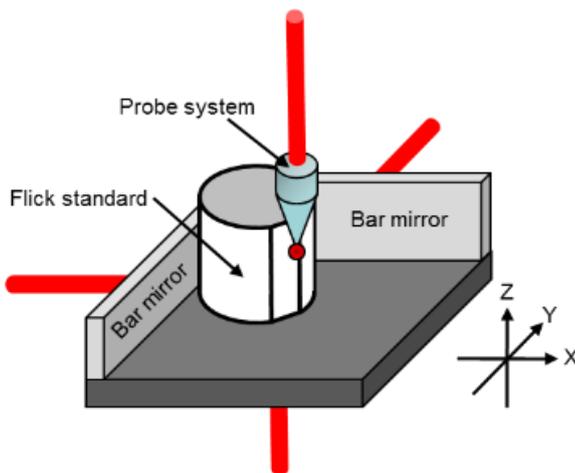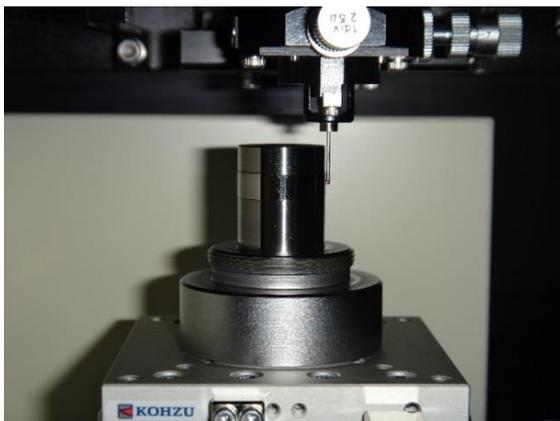

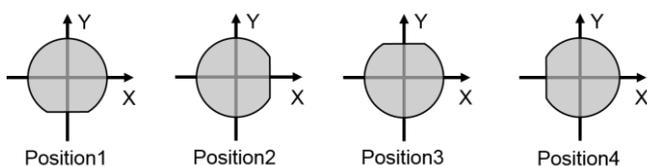Fig. 2: Schematic view of CMM

Fig. 3: Schematic view of CMM

Fig. 4: Measurement orientation of flick standard

3. CALIBRATION OF FILCK STANDARD

We measured a flick standard manufactured by Kosaka Laboratory Ltd. The measurement procedure is as follows:

(i) Decision of the measurement height

We calibrated the Z-axis center of the flick part. When the probe center does not coincide with the optical axis, it is Abbe error. The flick standard was set so that the measurement area was coincide with the optical axis less than 3 mm.

(ii) Alignment

The flick standard was set on a biaxial tilt stage. If the cylindrical axis of the flick standard is inclined with respect to the Z-axis, the cross-sectional circle is be an ellipse. We adjusted the inclination of flick standard of each XY-axes less than 2.5×10^{-4} rad.

(iii) Measurement

We measured five cross sectional circle of flick standard. The measurement was performed at 0.25 mm pitch around the calibration height (± 0.5 mm). The measurements were repeated three times.

(iv) Change the orientation

The flick standard was arranged in four position to eliminate a systematic error of the CMM as shown in figure 4[3]. The Flick standard was adjusted with each orientation so that the normal vector of its flat part coincided within 1 degree to the X- or Y-axis.

Table 1 shows the specification of the flick standard and the measurement conditions. Table 2 shows the measurement result of flick values at each orientation and height. We calculated the calibration value of the flick standard by the mean value of all measurements results. Figure 5 and 6 show the dispersion of the mean flick value of the each orientation and height, respectively.

Table 1: Specification of flick standard and measurement conditions

Nominal diameter of flick standard	19 mm
Nominal flick value	15 μm
Evaluation angular range θ_f	6.4 °
Probe diameter	1 mm
Sampling points	7000 points/cycle
Scanning speed	0.5 mm/s
Scanning range in Z direction	± 0.5 mm
Scanning pitch in Z direction	0.25 mm

Table 2: Measurement result of flick standard

| Measurement Number		n1	n2	n3
Position 1	H(-0.5)	15.030	15.033	15.038
	H(-0.25)	15.031	15.035	15.040
	H(0)	15.045	15.049	15.053
	H(+0.25)	15.045	15.046	15.039
	H(+0.5)	15.045	15.037	15.040
Position 2	H(-0.5)	15.023	15.034	15.027
	H(-0.25)	15.026	15.030	15.029
	H(0)	15.038	15.038	15.037
	H(+0.25)	15.035	15.041	15.040
	H(+0.5)	15.039	15.038	15.034
Position 3	H(-0.5)	15.029	15.036	15.031
	H(-0.25)	15.043	15.038	15.038
	H(0)	15.039	15.042	15.040
	H(+0.25)	15.047	15.045	15.042
	H(+0.5)	15.051	15.040	15.058
Position 4	H(-0.5)	15.034	15.026	15.035
	H(-0.25)	15.022	15.033	15.034
	H(0)	15.038	15.030	15.021
	H(+0.25)	15.039	15.038	15.044
	H(+0.5)	15.029	15.028	15.028
Mean value: 15.037				
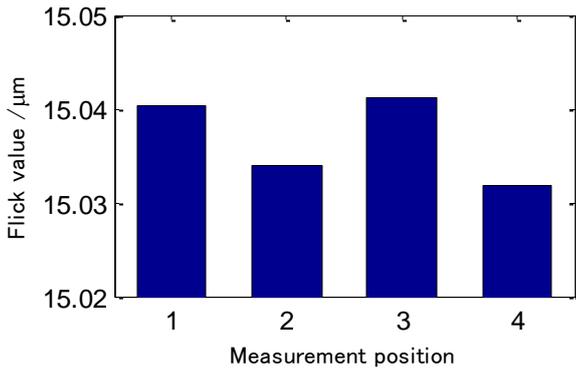
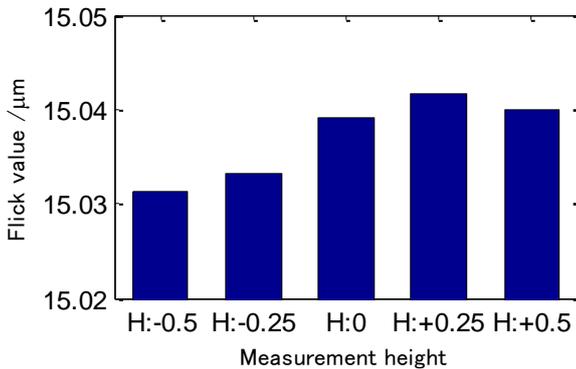Fig. 5: The variation of the measured radius by the alignment error of the flick standard

Fig. 6: The variation of the measured radius by the alignment error of the flick standard

4. UNCERTAINTY IN MEASUREMENTS

We estimated the uncertainty in measurement of the flick standard using the CMM in the previous section. Table 3 shows the uncertainty budgets. Five major uncertainty components were estimated as follows:

4.1 Uncertainty of the Interferometer
4.1.1 Laser wavelength, u_1-u_9

The coordinate of the CMM is obtained by the laser interferometer. The laser source used in the CMM is a stabilized He-Ne laser. The wave length of the laser of the CIPM recommended value[4], 632.9908 nm with a relative standard uncertainty of 1.5×10^{-6} in vacuum, was used. The refractive index of air of the laser wavelength was calculated using the Ciddor equation[5]. The measurement condition of the temperature was 20.7 ± 0.2 ℃. The other parameters were used as a constant values: air pressure 101.325 ± 5 kPa, 40 ± 10 % and 450 ± 50 ppm, by the experience. The influence of the measurement conditions were treated as uncertainty sources. The standard uncertainty was assumed as a rectangular probability distribution.

4.1.2 Cosine error, u_{10}

Measurement values of XYZ-coordinate include the cosine error of a misalignment between the laser axis and the stage axis. The misalignment angle was less than 1×10^{-4} rad. The cosine error of the standard uncertainty was assumed as a rectangular probability distribution.

4.2 Uncertainty of the probing, u_{11}
4.2.1 Deformation of flick standard

The flick standard is deformed by the probing force. We calculated the deformation value. The calculation conditions were as follows:
- the probing force: 0.3 mN,
- the radius of probe : 0.5 mm,
- the radius of cylinder: 9.5 mm,
- the material of probe: ruby (Young's modulus: 400 Gpa and Poisson's ration 0.34),
- the material of flick standard : steel (Young's modulus: 210 Gpa and Poisson's ration 0.29).

The indentation depth of the cylindrical part and flat part were 1.6 nm and 1.6 nm, respectively. The influence of the flick value is the difference between the deformations of the cylindrical part and flat part. The influence of the deformation was negligible.

4.2.2 Probing error

The probing system is calibrated by measuring a reference sphere; however, it includes the form error of the reference sphere, the probe sphere and bar mirrors, respectively. It is difficult to separate each error components. The RMS (root-mean-square) value of the measurement result of the reference sphere was treated as uncertainty source of the probing system.

4.3 Uncertainty of alignment
4.3.1 Alignment of the specimen, u_{13}

If the cylinder axis of the flick standard and the Z-axis of the CMM are different, the cross-section circle of the flick standard with respect to the Z-axis is be an ellipse. The contact vector of the probe is not perpendicular to the Z-axis as shown in figure 7. We denote the variation of the measured radius of the circle by δr_c as follows:

Table 3: Budget table of uncertainty of measurement of flick standard

NO.	Factor		$u_i(L) = (\partial f / \partial x_i) \cdot u(x_i)$
1		Wave length of laser	0.023 nm
2		Refractive index of air (Temperature)	0.002 nm
3		Refractive index of air (Pressure)	0.12 nm
4		Refractive index of air (Humidity)	0.001 nm
5		Refractive index of air (CO$_2$ densicty)	0.000 nm
6	Interferoeter	Ciddor equation	0.000 nm
7		Dead path (Temperature)	0.599 nm
8		Dead path (Pressure)	8.38 nm
9		Dead path (Humidity)	0.543 nm
10		Dead path (CO$_2$ density)	0.089 nm
11		Cosine error	0.075 nm
12		Probing error	9.83 nm
13	Alignment	Alignment of specimen	0.97 nm
14		Abbe error	17.3 nm
15		Thermal expansion	0.042 nm
16		Dispersion of measured cross-section	1.83 nm
17	Measurement	Systematic error of CMM	2.22 nm
18		Repeatability	0.68 nm
Combined standard uncertainty			21.8 nm
Expanded uncertainty ($k = 2$)			43.7 nm

$$\delta r_c = r_c \left(\frac{1}{\cos\theta_e} - 1 \right) + r_p \left(\frac{1}{\cos\theta_e} - 1 \right)$$
$$\approx \frac{1}{2}(r_c + r_p)\theta_e{}^2, \tag{3}$$

where r_p is the radius of the probe and θ_e is the inclination angle between the cylinder axis and the Z-axis.

We aligned the flick standard so that the orthogonal orientated inclination angle of the cylinder axis with respect to the Z-axis orthogonal two axis was less than 2.5×10^{-4} rad. The variation of the measured radius was treated as uncertainty source.
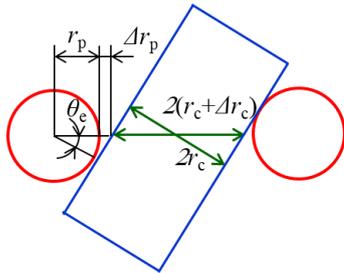

Fig. 7: The variation of the measured radius by the alignment error of the flick standard

4.3.2 Abbe error, u_{14}

The measurement system of the CMM is according to the Abbe principle. When the flick standard is measured, the probe moves $\pm$ 3 mm or less in the Z-axis direction from the optical axis and the measurement coordinates has abbe error. The evaluation of the motion error of the XY-stage is a future work. The maker specification of the pitching error and yawing error of the X and Y axes is $\pm 1.0 \times 10^{-5}$ rad at full stroke. The uncertainty of measurement by the Abbe error was calculated as follows:

$$\delta L_a = \frac{dz \times \sqrt{4 \times \theta_a{}^2}}{2\sqrt{3}}, \tag{4}$$

where δL_a was the abbe error, dz was the moving distance of the probe from the optical axis and θ_a was the motion error (pitching an yawing of the X and Y axes).

4.4 Uncertainty of thermal expansion, u_{15}

We corrected the thermal expansion of the flick value. The variation of temperature, the measurement uncertainty of temperature and the uncertainty of the thermal expansion coefficient are error factors of the correction. The temperature condition was 22.7 °C. T_0 is the deviation from 20 °C ($T_0 = 2.7$ K). The variation of the work temperature T_v was ± 0.2 K. The measurement uncertainty of thermometer T_c was 5.7 mK. The standard uncertainty of the coefficient of thermal expansion u_{CTE} was 1.0×10^{-6}. The standard uncertainty of the flick value ($h = 15$ μm) was calculated as follows:

$$u_{15} = \left(T_0 + \frac{T_v}{\sqrt{3}} + T_c \right) \times u_{CTE} \times h. \tag{5}$$

4.5 Uncertainty of measurement, u_{16-18}

We calculated the dispersion of measured cross-section, the dispersion of orientations (i.e. systematic error of the CMM) and repeatability from the expectation value of dispersion by the two-way analysis of variance.

5. CONCUKUTION

We calibrated a flick standard using an ultra-high accurate coordinate machine (CMM) to ensure the measurement uncertainty within 0.1 μm. In this paper, we described the calibration procedure and its analysis method of measurement uncertainty. We measured a flick standard

which the nominal diameter was 19 mm and the nominal flick value was 15 μm. We adopted the multiple orientation technique to eliminate the systematic error of the CMM. The calibration result was 15.04 ± 0.05 μm. We could calibrate the flick value within 0.1 μm. When a flick standard which the diameter 90 mm and the flick value is 500 μm is calibrated, the expanded measurement uncertainty U_{95} is less than 0.05 μm.

In this paper, we calculated the flick value based on the least square method. The next task is how to evaluate the probe magnification of roundness measuring instruments using the calibrated flick value.

ACKNOWLEDGEMENTS

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