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STEP-GAUGE CALIBRATION USING AN INTERFEROMETRIC COORDINATE MEASURING MACHINE AND THE UNCERTAINTY

Sonko OSAWA, Toshiyuki TAKATSUJI and Tomizo KUROSAWA

Dimensional Standards Section, Lengths and Dimensions Division,
National Metrology Institute of Japan (NMIJ),
National Institute of Advance Industrial Science and Technology (AIST),
Tsukuba, Ibaraki, JAPAN

Abstract – There are many kinds of geometrical gauges used for calibration of machine tools and coordinate measuring machines (CMMs). A step-gauge is a kind of calibration gauge. It consists of many short gauge blocks and a base bar. Gauge blocks were directly calibrated by an interferometer using method of exact fraction. The method, however, does not apply to the calibration of step-gauges because of their complicated structure. The calibration works are very important missions in national metrology institutes (NMIs). We developed the step-gauge calibration system that consisted of a CMM and an interferometer. We describe the system scheme of a step-gauge calibration system using a conventional CMM combined with an interferometer and the evaluation of the measurement uncertainty. The uncertainty in measurement using this system is about 0.5 µm (k=2) for 1-meter measurement.

Keywords: step-gauge calibration, uncertainty, Coordinate measuring machine, traceability

1. INTRODUCTION

There are many kinds of geometrical gauges, for example gauge blocks, step-gauges, ball-bars, ball-plates and hole-plates, etc., used for checking the accuracies of machine tools and coordinate measuring machines (CMMs) and the calibration of them. Especially, gauge blocks are usually used for checking machine accuracies and calibrations of calipers, micrometers, dial gauges and so on. The gauge blocks, however, are not so useful for checking the accuracy of CMMs. We need a lot of different size gauge blocks to check a CMM. So, step-gauges are mainly used for checking the accuracy of CMMs. A Step-gauge consists of many short gauge blocks and a base steel bar. So, we obtained a lot of information to check the accuracy of a machine. Gauge blocks are directly calibrated by an interferometer using method of exact fraction. The method does not, however, apply to the calibration of step-gauges because of their complicated structure. Gauge calibration works are very important missions in national metrology institutes (NMIs). We developed a step-gauge calibration system that consists of a CMM and an interferometer. The system is simple, easy to handle, but precise. In this paper, we describe the system scheme of a step-gauge calibration system using a conventional CMM combined with an interferometer and the evaluation of the measurement uncertainty.

2. AN INTERFEROMETRIC COORDINATE MESURING MACHINE

We developed an instrument for step-gauge calibration. It consists of an interferometer (Agilent Technology: Agilent 5529A) and a coordinate measuring machine (Brown & Sharpe PMM866P). We call the instrument "interferometric coordinate measuring machine". Figure 1 shows the schematic diagram of the interferometric coordinate measuring machine. The CMM is used to the precise moving table. And also, it has a good probe head. The probing system can detect the position of a gauge very precisely. It is very important for the step-gauge calibration.

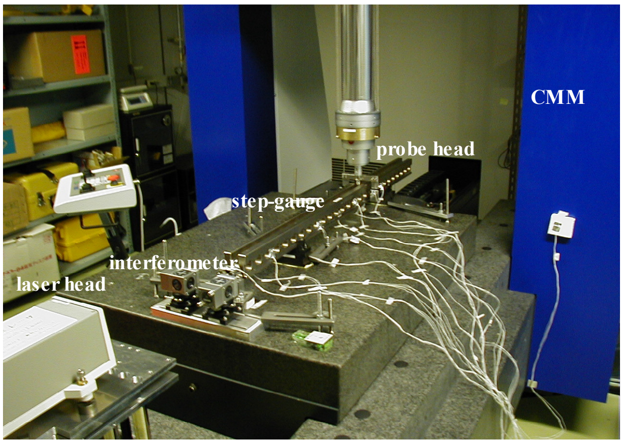

Fig. 1. Interferometric coordinate measuring machine

We had two choices to develop a step-gauge measuring instrument. One is a single path interferometer system. Another is a four-path interferometer system. Figure 2 shows the schematic of the single path interferometer system and figure 3 shows the four-path interferometer system. Firstly, we had an experiment of measuring a step-gauge by a single-path interferometer system. The cube corner is located in the moving table of the CMM and the interferometer which consists of a polarized beam splitter and a cube corner is located in front of a laser head. The interferometer is independent of the moving table of the CMM. We measure the distance between the interferometer and the cube corner attached to the table. Table 1 shows the result. We had three times measurements. The result shows

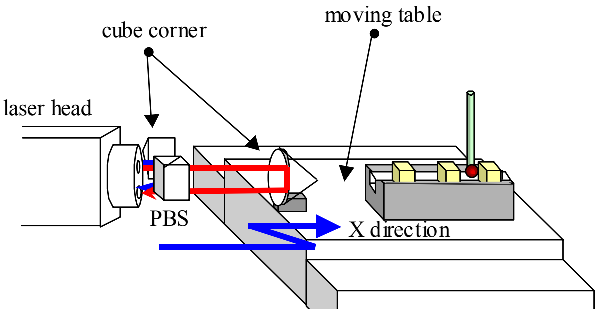

Fig. 2. Setup for single-path interferometer system

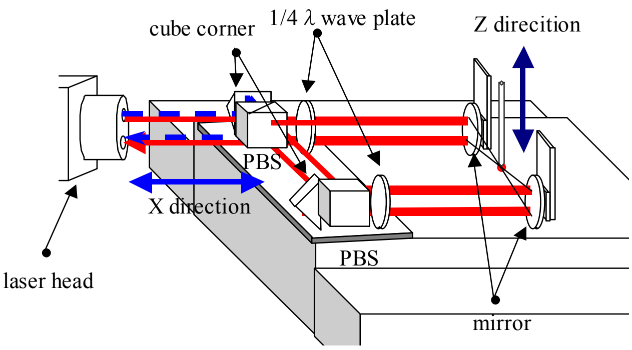

Fig. 3. Setup for four-path interferometer system

TABLE 1. Results of measurements using single-path interferometer [mm]

	1 forward	1 reverse	2 forward	2 reverse	3 forward	3 reverse
0	-0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
20	20.0016	20.0019	20.0020	20.0017	20.0009	20.0016
40	40.0044	40.0049	40.0045	40.0047	40.0041	40.0043
60	60.0059	60.0061	60.0058	60.0061	60.0056	60.0059
80	79.9764	79.9762	79.9763	79.9766	79.9758	79.9762
:	:	:	:	:	:	:
640	640.0980	640.0982	640.0976	640.0980	640.0979	640.0980
660	660.1002	660.1004	660.0999	660.1001	660.0998	660.1001
680	680.0707	680.0706	680.0705	680.0707	680.0706	680.0704
700	700.0719	700.0718	700.0718	700.0717	700.0719	700.0715
720	720.1998	720.2000	720.1999	720.2000	720.1997	720.1995

that the deviation of the each point measurement is large. It was caused by influence of the machine vibration, the pitching and yawing motion of the moving table and so on. It comes from the long measuring loop. So, we use the four-path interferometer system for step-gauge calibration. The four-path interferometer method has been often used for step-gauge measuring systems [1][2]. This system is well known to be able to cancel the "Abbe's error" automatically. The four-path interferometer system consists of two polarized beam splitters, two cube corners, two 1/4 λ wave plates and two mirrors. The mirrors are attached to the probing system side by side. The centre of probe tip is located in the centre of the four beams. Therefore, if the system had a pitch and a yaw error, the error would be automatically compensated. And also, the resolution of the system is four times better than the single-path system.

The interferometer synchronizes the signal of the CMM's probing system. We are able to obtain the touch

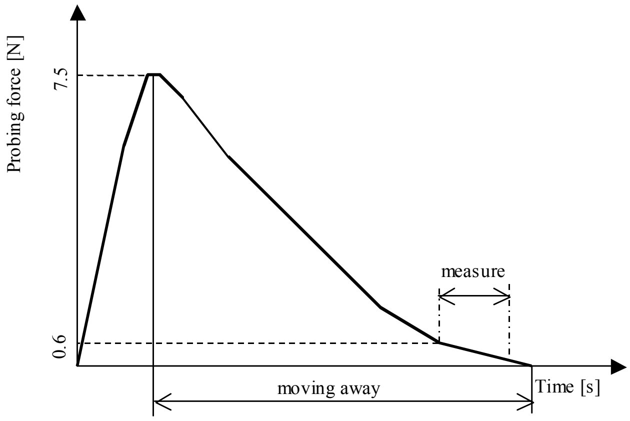

Fig.4. Probing characteristic

signal from CMM's probing system. Figure 4 shows the probing characteristic of our CMM. The probe pushes in the face of a step-gauge until the probing force becomes to 7.5 N and then, it moves away from the face of the gauge. From the probing force become to 0.6 N, we obtain a good linearity and the CMM generate some pulses. The interferometer synchronizes the pulses. So, we can make the relationship between analogue signal of the probing system and the measured distance by the interferometer using least-squares method for obtaining the touch signal.

The probing system is calibrated by gauge block, of which size is 10 or 20 mm. It is the same size of the step-gauge pitch. The gauge block is mounted at just back of the optics of the interferometer. It reduces the dead path error of the interferometer. We obtain the deflection of the probe stylus, the diameter of the probe sphere and so on from the probe calibration. We measure the gauge block ten times and then, we calculate the each relationship between analogue signal of the probing system and the measured distance by the interferometer using least-squares method. And then, we make graphs of the relationship and obtain the least gap point of the difference between the graphs. The point is the threshold of the probing.

After the probe calibration, we start the step-gauge calibration. Table 2 shows the results of step-gauge measurement using four-path interferometer system. The results show the small deviation between three measurements. The deviation is only 0.1 µm. It is better than the results by the single-path interferometer.

TABLE 2. Results of measurements using four-path interferometer [mm]

	1 forward	1 reverse	2 forward	2 reverse	3 forward	3 reverse
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20	20.0014	20.0015	20.0014	20.0014	20.0014	20.0014
40	40.0045	40.0045	40.0045	40.0045	40.0044	40.0044
60	60.0058	60.0058	60.0058	60.0058	60.0058	60.0058
80	79.9760	79.9760	79.9760	79.9760	79.9760	79.9760
:	:	:	:	:	:	:
640	640.0970	640.0970	640.0970	640.0970	640.0970	640.0970
660	660.0992	660.0992	660.0992	660.0992	660.0992	660.0992
680	680.0698	680.0698	680.0698	680.0698	680.0698	680.0698
700	700.0711	700.0711	700.0711	700.0711	700.0711	700.0711
720	720.1992	720.1992	720.1991	720.1991	720.1991	720.1991

3. ENVIRONMENT MEASUREMENT

An environment measurement is very important for an interferometer measurement. Specially, we use the four path interferometer system for a step-gauge measurement. So, we have to measure the temperature, the pressure, the humidity and the concentration of CO_2 gas of the air. We use platinum (Pt) sensors for the temperature measurement. We use two Pt sensors for the air temperature measurement and eight sensors for step-gauge temperature measurement. It is well known that Pt sensors are heated up by themselves. It depends on the electric current. We had some experiments to observe the influence. We prepared three sensors and attached the sensors to a small cube copper as straight. We changed the current of the centred sensor from 0.1 mA to 0.5 mA and observed the heat influence using other two sensors. As a result, we did not obtain the influence. Next, we changed the current of the centred sensor to 1 mA. We obtained that the sensor was heated up10 mK. We usually use 0.5 mA current, therefore we think that the influence does not affect to step-gauge measurement.

We use a digital pressure measuring equipment using silicon resonant sensor for air pressure measurement and a optical dew point measuring equipment for humidity measurement.

4. CALBRATION PROCEDURE

Figure 5 shows the flow chart of a step-gauge calibration procedure. We calibrate step-gauges according to the procedure.

1. Cleaning up a step-gauge

The cleaning up procedure is very important for all measurements.

2. Gauge face inclination measurement

The inclination measurement of the face of step-gauge is very important for the calibration. The step gauge consists of a lot of short gauge blocks and a base steel bar. The gauge blocks sometimes have large inclinations. Therefore, we should check the inclination.

3. Gauge alignment

We use a dial gauge for the step-gauge alignment. We attach the dial gauge to the CMM's ram and then move the CMM table and trace the side face of the step-gauge. We continuously do this alignment procedure until a few micrometer alignments.

4. Affix temperature sensors on a gauge and waiting

Temperature is the most important for gauge calibration. Therefore, we spent a lot of time to wait the stable temperature.

5. Measurement

We measure the step-gauge on five sequences. One sequence includes a forward measurement and a backward measurement. The forward measurement starts from the front side to posterior side and backward measurement starts from posterior side. We have an environment measurement before the step-gauge measurement. Then, we have the probe calibration before the forward measurement. After the backward measurement, we have the probe calibration and environment measurement again.

6. Calculation of calibration values

We use the average value of two environment measurements for the calculations of the step-gauge calibration values. The values are calculated using Edlen's equation.

7. Uncertainty estimation

We estimate the uncertainty of the calibration measurement according to the GUM (Guide to the expression of uncertainty in measurement) [3].

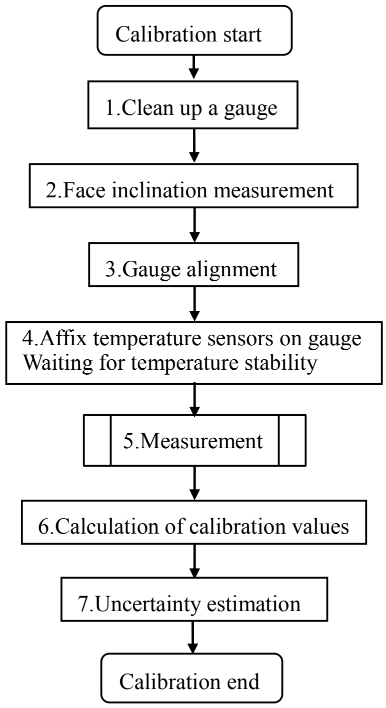

Fig.5. Flow chart of a step-gauge calibration procedure

5. UNCERTAINTY EVALUATION

We evaluated the uncertainty in measurement in accordance with the GUM. The calibration value is obtained by the equation (1).

$$l_{SG} = m\lambda - L\alpha_{SG}\Delta t_{SG} + \delta_{ASG} + \delta_{AS} + \delta_P + \delta_G + \delta_I + \delta_D \qquad (1)$$

here,

l_{SG} : Distances of step-gauge at the reference temperature of 20 °C

m : Number of wavelengths

λ : Laser wave length

L : Nominal values of step-gauge

α_{SG} : Thermal expansion coefficient of step-gauge

Δt_{SG} : Difference between step-gauge temperature and reference temperature 20 ℃

* Independent of thermal expansion

δ_P : Reproducibility of probing

δ_G : Uncertainty of gauge block calibration

δ_I : Inclination of step-gauge pin

δ_D : Deformation from probing

* Dependent of thermal expansion

δ_{ASG} : Uncertainty from step-gauge alignment

δ_{AS} : Uncertainty from laser alignment

The uncertainty of step-gauge calibration is calculated by the equation (2).

$$u^2(l_{SG}) = m \times u^2(\lambda) + L \times u^2(\alpha_{SG}) \times \Delta t_{SG} + L \times \alpha_{SG} \times u^2(\Delta t_{SG}) \quad (2)$$
$$+ u^2(\delta_{ASG}) + u^2(\delta_{AS}) + u^2(\delta_P) + u^2(\delta_G) + u^2(\delta_I) + u^2(\delta_D)$$

The uncertainties are divided into independent of thermal expansion uncertainties or dependent on thermal expansion uncertainties.

Table 2 shows the uncertainty components in step-gauge calibration.

Table 2 Uncertainty components in step-gauge calibration

No.	Sources of uncertainty	Magnitude	Type	Uncertainty
	Independent of thermal expansion			
1	Probing	0.05 μm	A	0.050 μm
2	Calibration of probe	0.02 μm	B	0.020 μm
3	Uncertainty of GB	0.012 μm	B	0.012 μm
4	Inclination of pin	0.018 μm	B	0.018 μm
5	Difference of material	0.035 μm	B	0.020 μm
	Combined standard uncertainty			0.061 μm
	Dependent on thermal expansion			
6	Temperature measurement	5 mK	B	0.034 μm
7	Temperature distribution	20 mK	A	0.136 μm
8	Wavelength (frequency)	1.5 MHz	B	0.002 μm
9	Wavelength (temperature)	95 mK	A	0.053 μm
10	Wavelength (air pressure)	53 Pa	A	0.081 μm
11	Wavelength (humidity)	0.64 %	A	0.008 μm
12	Wavelength (CO_2)	50 ppm	B	0.004 μm
13	Error of cosine (gauge)	0.1 mm/720 mm	B	0.007 μm
14	Error of cosine (laser)	0.1 mm/720 mm	B	0.007 μm
15	Thermal expansion coefficient	1.0E-6 /K	B	0.141 μm
	Combined standard uncertainty			0.222 μm

The uncertainty in measurement of the step-gauge calibration using our instrument is

$$U = k \times \sqrt{0.06^2 + (0.22L)^2} \text{ (μm; L:m; } k\text{:coverage factor).}$$

The biggest source is the uncertainty of probing in independent of thermal expansion and the uncertainty of the thermal expansion coefficient of the step-gauge in dependent on thermal expansion.

6. CONCLUSIONS

We developed the instrument for step-gauge calibration. We described the system scheme of a step-gauge calibration system using a conventional CMM combined with an interferometer in this paper. And we estimated the uncertainty in measurement of the step-gauge calibration. The uncertainty in measurement using our system is about 0.5 μm (k=2) for 1-meter measurement.

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Authors: Sonko OSAWA, Toshiyuki TAKATSUJI and Tomizo KUROSAWA,
Dimensional Standards Section, Lengths and Dimensions Division, National Metrology Institute of Japan(NMIJ), National Institute of Advance Industrial Science and Technology(AIST), 1-1-1 Umezono Tsukuba Ibaraki, 305-8563, JAPAN, Phone: +81-298-61-4368, Fax: +81-298-61-4042, E-mail: sonko.osawa@aist.go.jp