Determination of the phase-change correction used for gauge block calibration by optical interferometry technique

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Abstract

Phase-change corrections used for gauge block calibration for gauge block and base plate of various materials were investigated. Experimentally determined phase-change corrections obtained from three different gauge block interferometer (GBI) were compared. Experimental result illustrate that phase-change correction is characteristic of the interferometer system. The values are appeared to be inconsistent difference for all materials. Gauge block calibration after applying phase-change correction for all gauge block interferometer system was compared and En ratio are well below 1.

Keywords: Phase-Change Correction, Gauge Block.

1 Introduction

Gauge blocks are one of the most important artifacts used to maintain traceability in dimensional metrology. They play a major role as a standard of length. In order to support an increasing need for the higher measurement accuracy, reducing uncertainty of the length standard is one of the solutions. Gauge blocks are generally calibrated using laser interferometer achieving uncertainty of 20-30 nm. [1] One of major source of uncertainty is phase-change correction error. This error is due to the fact that gauge block must be wrung on the platen. Thus, error compensation should be applied for this optical technique in order to achieve high accurate measurement. [3-4] this compensation is known as the phase-change correction.

There are numbers of method for phase-change correction determination, stacking method, measurement using stylus instrument and base-plate method for instance. In many international comparisons, number NMIs had report their estimated phase-change corrections. However reported phase-change corrections are varied widely even though the measurement results of GB's length are well consistent. [5-7] In this paper phase-change corrections from 3 gauge block interferometer systems were determined and was compared in order to understand characteristic of phase-change correction.

2 Experimental

Phase-change corrections were investigated according to stacking. Five gauge blocks (GBs) of the same material were wrung on base plate (BP) and measured individually. Then all gauge blocks were wrung together on the base plate of the same material in a stack and measured as a single gauge block (stacking gauge block).

2.1. Stacking method

The true length of an individual gauge block (l_i) can be explained as in Eq. (1) where $l_{o,i}$ and ϕ are the optical length of an individual GB and the phase-change correction, respectively. [1-3]

$$l_i = l_{o,i} + \phi \tag{1}$$

$$l_s = l_{o,s} + \phi \tag{2}$$

The true length of the stacked gauge block can be determined by correcting the optical length of stacked GB $l_{o,s}$ with the phase-change correction.

$$l_s = \sum_{i=1}^{n} l_{o,i} + n \cdot \phi \tag{3}$$

Length of the stacked GB can be rewriting as in Eq. (3) where n is number of GB used in the experiment.

Thus, the difference in the measured length of the stacked gauge block and the summation of the measured length of the individual gauge blocks is the phase-change correction as shown in Eq. 4.

$$\phi = \frac{1}{n-1}\left[l_{o,s} - \sum_{i=1}^{n} l_{o,i} \right] \tag{4}$$

2.2 Apparatus

Gauge blocks used in this paper are made of steel longer than 10 mm. Thus, bending error can be neglected. Gauge blocks were wrung on quartz and steel base plates. Lengths of gauge blocks were measured by the 3 gauge block interferometer system. Technical details of each GBI system are lists in Table 1. Gauge blocks were measured in the control environment chamber where the temperature was kept constant with variation of temperature less than 0.2 ^{o}C. Interference fringes of gauge block that wrung on base plate as demonstrated were analyzed using fringe analysis program.

Table 1: Technical details of each GBI system

Abbreviation	**Manufacturer**	**Model**	**Interferometer type**	**Analysis method**
GBI 1	Mitutoyo	GBI 1	Twyman–Green	Fraction Fringe
GBI 2	Mitutoyo	GBI 2	Twyman–Green	Phase shifting Interferometer
GBI 3	NIMT	GBI 3	Michelson	Fraction Fringe

3 Result and Discussion

Optical lengths of stacked and individual gauge blocks were measured using gauge block interferometer. According to Eq. 4, phase-change corrections of gauge block and base plate can be determined and the results are summarized in Table 2.

The maximum difference in phase-change correction among 3 systems is 63 nm for steel gauge block wrung on quartz base plate. Moreover, phase-change corrections for GBI 1 and GBI 2 are quite different even they are both manufactured by the same manufacturer and are constructed based on Twyman-Green interferometer.

Table 2: Results of phase corrections compared between GBI 1, GBI 2 and GBI 3.

Unit in nm

GB / BP	GBI 1	GBI 2	GBI 3
	Results		
Steel/Steel	+4	+2	-4
Steel/Quartz	+45	+24	-18

The measurement uncertainty of phase-change correction was evaluated as details in Table 3. The standard uncertainty of 4.4 nm was obtained. Combining the measurement uncertainty of phase-change correction to the uncertainty of GB measurement, $U_{95\%}$ at 28 nm, 29 nm and 21 nm for GBI 1, GBI 2 and GBI 3 are observed, respectively.

Table 3: Components of combined standard uncertainty of phase-change correction.

Unit in nm

Source of Uncertainty	Contribution Uncertainty, u_i (y)
Fringe fraction; u(ε)	1.39
Wringing influence; $u(l_w)$	6
Wave front error; $u(l_A)$	3.46
Gauge geometry correction $u(l_G)$	1.62
Uncertainty, $u(l_\phi)$	4.4

Optical lengths of gauge blocks were corrected by phase-change correction and temperature compensation in order to determine the physical length of GB at 20 °C. The measurement results measured by 3 gauge block interferometer systems together with their measurement uncertainties are summarized in Table 4.

Table 4: Measurement results from 3 systems

Unit in nm

GB / BP	Size, mm	GBI 1		GBI 2		GBI 3	
		Dev.	$U_{95\%}$	Dev.	$U_{95\%}$	Dev.	$U_{95\%}$
S/S	11	30	28	32	29	12	21
	12	-8	28	-11	29	-28	21
	13	5	28	9	29	13	21
	14	-3	28	10	29	10	21
	15	-20	28	-7	29	-17	21
S/Q	11	30	28	27	29	15	21
	12	-8	28	-13	29	-30	21
	13	5	28	18	29	1	21
	14	-3	28	14	29	2	21
	15	-20	28	-23	29	-14	21

GB=Gauge Block, BP=Base Plate, S=Steel, Q=Quartz

In order to investigate discrepancy in gauge blocks measurement by 3 different systems, reference values, $\overline{x}_{ref}$, together with their uncertainties, $u\left(x_{ref}\right)$, were calculated according to Eq. (5) and Eq. (6). Then, their equivalent ratio (En) for each system was determined according to Eq. (7). [8] The calculated reference values, their uncertainties and En values are summarized in Table 5. The En ratios for all measurements are well within 0.5 which indicate excellent agreement of the measurement results from all systems.

$$\bar{x}_{ref} = \left[\sum_{i=1}^{n} {x_i}\big/{u^2(x_i)}\right] \Bigg/ \left[\sum_{i=1}^{n} {1}\big/{u^2(x_i)}\right] \tag{5}$$

$$\frac{1}{u^2(x_{ref})} = \sum_{i=1}^{n} \frac{1}{u(x_i)} \tag{6}$$

$$En = \frac{x_i - x_{ref}}{\sqrt{u^2(x_i) + u^2(x_{ref})}} \tag{7}$$

Table 5: Equivalent ratio (En) from 3 GBIs compared with the reference values.

GB / BP	Size, mm	Reference value		En		
		Dev.	$U_{95\%}$	GBI 1	GBI 2	GBI 3
S/S	11	22	14.5	0.25	0.31	0.39
	12	-18	14.5	0.25	0.22	0.39
	13	10	14.5	0.25	0.03	0.12
	14	7	14.5	0.25	0.09	0.12
	15	-15	14.5	0.25	0.25	0.08
S/Q	11	22	14.5	0.25	0.15	0.27
	12	-20	14.5	0.25	0.22	0.39
	13	6	14.5	0.25	0.37	0.20
	14	4	14.5	0.25	0.31	0.08
	15	-18	14.5	0.25	0.15	0.16

4 Conclusion

Phase-change corrections for three different gauge block interferometers system were investigated. By employing stacking method, phase-change corrections for gauge block calibration were determined. We had successfully demonstrated that phase-change correction is not only characteristic of gauge block and base plate but also characteristic of the laser interferometer used. Although it is constant, but the value obtained from one system should not be applied to another system. The maximum difference observed is 63 nm which is much bigger than its standard uncertainty (4.4 nm). Even for gauge block interferometers constructed based on Twyman-Green interferometer, their phase-change corrections differ by 21 nm for steel gauge block wrung on quartz base plate. After applying phase-change correction to the optical length of gauge block, the physical length of gauge block can be determined. The degree of equivalents was determined and the results clearly show good agreement well within their measurement uncertainties.

5 References

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