Determination Model of Phase-Change Correction for High Precision Gauge Block Calibration

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Abstract

When gauge blocks are calibrated by the laser interferometer technique, phase-change corrections play a crucial role in the measurement uncertainties. In order to reduce the source of uncertainty, phase-change correction must be known and be compensated to the measured results. We present here a determination based on knowledge gained from the stacking method and the known value of phase correction of quartz. It is a fast and robust method. Phase-change correction of any pair of auxiliary plates and gauge blocks can be calculated by using our model. This method is suitable for the national metrological institutes (NMIs), calibration laboratories and industries where calibration of various gauge block materials are carried out and measurement uncertainty within 30 nm is adequate. The experimentally observed phase-change corrections were compared with the calculated values according to our model. The comparison illustrates a good agreement. The measurement uncertainty of gauge block calibration using our interferometer system is 24 nm.

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1. Introduction

Gauge blocks (GB) have been essential reference artefacts in manufacturing for decades because they have a simple geometry and also can provide very high accuracy for a reasonable price. Gauge blocks play a crucial role in maintaining traceability to the 'Metre' in dimensional metrology. The most accurate method for calibrating the length of gauge block is to use optical interferometer. However, interferometry technique measures the optical length rather than the mechanical length of the gauge block. Thus, error in the length measurement may be introduced due to difference in bulk and surface characteristics of the gauge block and the platen as illustrated in Fig. 1. These differences will give rise to a non-consistency between the length measured by an interferometer and that measured by a mechanical comparator. The length of gauge block is described in the standard ISO 3650:1998 as the perpendicular distance from any particular point on the gauge block and a plane surface of an auxiliary plate (AP) of the same material and surface texture upon which the measuring face has been wrung. [1] If auxiliary plates of other material (surface characteristic) are used, correction, known as phase-change correction, is needed to be taken into account. [1-2] Once the correction is known, measurement uncertainty can be minimized.
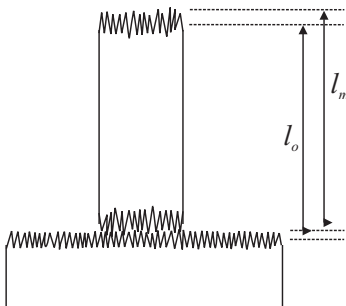

Fig. 1 Illustration of correction required for interferometric gauge block measurements. l_m and l_o are mechanical and optical length, respectively.

Steel is the traditional material for gauge blocks. Steel gauge blocks can provide many years of useful life if used and looked after carefully. Since steel is easy to get rusty and worn, manufacturers have introduced ceramic to gauge block manufacturing. Ceramic blocks have the advantage of never getting rusty and resisting scratches. Anti-corrosion treatment is not required when handled normally, resulting in simple maintenance and storage. Since the ceramic gauge blocks are very hard, they will not scratch and are highly resistant to burrs. They have an anti-magnetic nature which keeps away steel powders. Moreover, the thermal expansion coefficient of a ceramic gauge block is quite similar to that of a steel gauge block, resulting in no change of the measurement uncertainty due to the temperature effect.

With advances in metallurgy, applications of metallic carbides were applied to utilize the excellent wear resistance of gauge blocks. Tungsten carbide and chromium carbide are substantially more expensive than steel. In applications where wear is a troublesome factor, such as in some grinding areas, the superior wear resistance of carbide gauge blocks is frequently used. They have the advantage of being harder and longer wearing than steel. However, the differential in the coefficient of thermal expansion as compared to steel, the proneness to chipping and the not always homogeneous surface texture of sintered carbide blocks should be taken into account in the measurement uncertainty evaluations. Other materials, such as fused quartz, are sometimes selected to manufacture gauge blocks, but their actual use is very limited.

Even though gauge blocks are available in numerous types of material, auxiliary plates on the other hand are mostly made from either fused quartz or steel. Quartz and steel can be polished to the highest degree of smoothness. The transparency of quartz has an advantage for checking the proper wringing of gauge blocks. The coefficient of

thermal expansion of steel yields the smallest error caused by deviation and variation of temperature. Therefore, in order to calibrate gauge blocks by using a laser interferometer technique, gauge blocks are mostly wrung on either steel or quartz auxiliary plates. To achieve measurement uncertainty of 20- 30 nm, phase-change correction must be compensated to the measured length value. [2-4]

There are numbers of method for phase-change correction determination, stacking method, measurement using stylus instrument and base plate method for instance. Although numbers of NMIs reported their estimated phase-change corrections, disagreements were observed. [5-8] The reason for this fact is that phase-change correction is the characteristic property of the individual gauge block. Gauge blocks of the same material may not have the same surface texture. Moreover, many comparison results have also shown that each measuring system can yield different phase-change correction of the same gauge block. [3, 7] In order to achieve the nanometer scale uncertainty, phase-change correction of each specific block should be experimentally found for each gauge block interferometer system. As such, techniques used to quantify this correction have improved over the years. [9-14] The measuring system with the smallest uncertainty so far uses an integrating sphere. The total integrating scatter (TIS) is defined as the ratio of the diffuse reflectance to the total reflectance which is directly proportional to the surface roughness of the gauge block. The advantage is that phase correction of every gauge block can be calibrated and not just an average of the set.

In this paper, we report a new approach to determine phase correction of material based on the stacking method. The new method is quick and easy to use and phase-change corrections of all material can be estimated with adequate accuracy.

2. Material and Methods

Gauge blocks used in this paper are longer than 10 mm. Thus, bending error is negligible. There are steel, ceramic and tungsten carbide gauge blocks. Auxiliary plates are quartz, steel, ceramic and tungsten carbide. Phase-change corrections were investigated according to the stacking method. Lengths of stacked and individual gauge blocks were measured by the gauge block interferometer, manufactured by Mitutoyo, model GBI. Two frequency stabilized He-Ne lasers were used as the illumination giving wavelengths of 633 nm (red) and 543 nm (green). Both lasers have frequency stability in order of 10^{-9}. The environment in the measurement chamber was controlled and the temperature was kept constant with temperature variation of less than 0.2 $^{\circ}$C. Interference fringes of a gauge block wrung on an auxiliary plate were analysed using a fringe analysis program. Accuracy of this gauge block interferometer according to manufacturer is 20 nm.

For the stacking method experiment, five gauge blocks of the same material were wrung on an auxiliary plate. Then all the gauge blocks were wrung together on the auxiliary plate of the same material in a pack and measured as a single gauge block as shown in Fig. 2.
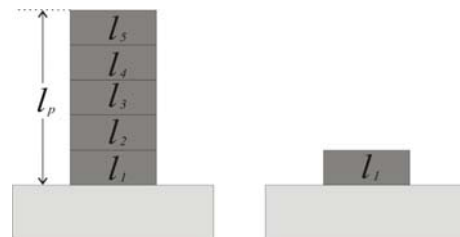

Fig. 2 Stacking method experiment.

Measured length of individual gauge block (l_i) and packed gauge block can be written as in equation (1) and (2) where $l_{o,l}$, $l_{o,p}$ and ϕ is the optical length of individual block, optical length of packed block and phase-change correction, respectively. [2-4]

$$l_i = l_{o,i} + \phi \qquad (1)$$

$$l_p = l_{o,p} + \phi \qquad (2)$$

Measured length of the packed gauge block can be determined by summing the optical lengths of all gauge blocks and phase-change correction where n is number of gauge block used, n = 5, as in equation (3).

$$l_p = \sum_{i=1}^{n} l_{o,i} + n \cdot \phi \qquad (3)$$

By simply substituting equation (2) and (3), phase-change correction can be determined according equation (4).

$$\phi = \frac{1}{n-1} \left[l_{o,p} - \sum_{i=1}^{n} l_{o,i} \right] \qquad (4)$$

Phase-change correction is the difference between phase correction of a gauge block and an auxiliary plate which are the unique characteristics of the material.

$$\phi = \phi_{GB} - \phi_{AP} \qquad (5)$$

3. Results and Discussion

Packed and individual gauge blocks were measured by using the gauge block interferometer system. According to equation (4), phase-change corrections of steel, ceramic and tungsten carbide gauge blocks wrung on steel, quartz, ceramic and tungsten carbide auxiliary plates were determined and are summarized in Table 1.

Since the phase correction of quartz is equal to zero [15-16], the phase-change correction that is obtained from the steel gauge block wrung on a quartz auxiliary plate is equivalent to the phase correction of the steel gauge block (+45 nm) according to equation (5). For the steel gauge block wrung on a steel plate, phase-change correction of +3.8 nm was obtained. Following equation (5) and knowing that the phase correction of steel gauge block is +45 nm, the phase correction of steel auxiliary plate is +48.8 nm. Thus, the phase correction of all gauge block material can be determined by using the same model once the phase correction of an auxiliary plate is known. In this paper, 3 different types of material of gauge block and 4 different types of auxiliary plate would need 12 ordinary stacking measurements to yield 12 phase-change corrections. By using our model, only 6 stacking measurements were required. The experimentally obtained phase-change corrections and the calculated values of 12 pairs of gauge blocks and auxiliary plates were summarized in Table 1. Excellent agreement was observed when comparing the calculated phase-change correction to the experimentally obtained values.

Table 1 Measured and calculated phase-change corrections in nm; Exp = Experiment, Cal. = Calculation.

GB \ AP	Steel		Quartz		Ceramic		Tungsten Carbide	
	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
Steel	+3.8	-	+45.0	-	+13.6	-	+23.7	-
Ceramic	-11.7	-9.5	+31.7	+29.5	-	-1.9	-	+8.2
Tungsten Carbide	-4.0	-4.2	+37.0	+37.2	-	+5.6	-	+15.9

The measurement uncertainty of the phase-change correction, $u(l_\phi)$, has been evaluated in accordance with the ISO Guide to the expression of uncertainty in measurement, GUM. [17] There are four components that contribute to the overall uncertainty. The uncertainty terms are considered individually and the total uncertainty is calculated as in equation (6) where n is number of gauge block used..

$$u^2\left(l_\phi\right) \approx \frac{(n+1)}{(n-1)^2}\left[\begin{array}{c} u^2\left(\varepsilon\right)+u^2\left(l_w\right) \\ +u^2\left(l_A\right)+u^2\left(l_G\right) \end{array}\right] \quad (6)$$

The other terms listed in equation (6) represent measurement uncertainty for the following components: fringe fraction $(u(\varepsilon))$, wringing influence $(u(l_w))$, wavefront error $(u(l_A))$ and geometry of gauge block $(u(l_G))$.

Table 2 summarized factors that have contribution to the uncertainty of the phase-change correction. They are fringe fraction reading error, wring reproducibility, wavefront error and geometrical error (flatness and parallelism) of gauge

block under-tested. Combining these uncertainty components in accordance with GUM yields a combined standard uncertainty with k = 2 of 4.6 nm for phase-change correction measurement.

Table 2 Components of combined standard uncertainty of phase-change correction.

Source of uncertainty	Contribution Uncertainty
Fringe fraction; $u(\varepsilon)$	2.41 nm
Wringing influence; $u(l_w)$	6 nm
Wavefront error; $u(l_A)$	3.46 nm
Gauge geometry correction $u(l_G)$	1.62 nm
Uncertainty, $u(l_\phi)$	4.6 nm

Table 3 Deviation of gauge blocks in μm; C = Ceramic, Q = Quartz, S = Steel and T = Tungsten Carbide

GB/AP	Reference deviation	Experiment		Calculation	
		Dev.	En	Dev.	En
C/Q	0.030	0.038	0.18	0.036	0.13
C/S	0.114	0.124	0.22	0.126	0.26
C/C	-0.039	-	-	-0.035	0.10
C/T	0.040	-	-	0.038	0.04
T/Q	-0.130	-0.130	0.00	-0.130	0.00
T/S	0.000	0.003	0.04	0.003	0.04
T/C	-0.030	-	-	-0.033	0.08
T/T	-0.030	-	-	-0.026	0.10

The experimentally measured and the phase-change corrections obtained from our determination model were applied to the gauge block calibration in order to reduce the measurement uncertainty. The results were summarized in Table 3 and compared with the length of gauge block calibrated by other NMIs (reference deviation). The En ratios were then calculated by using equation (7) is the in order to determine accuracy of this determination model. [18] x_{meas} and x_{cal} are phase-change correction obtained from the measurement and from the determination model, respectively. u_{meas} and u_{cal} are combined uncertainty of the phase-change correction obtained from the measurement and the determination model.

$$En = \frac{|x_{meas} - x_{cal}|}{\sqrt{(u_{meas} + u_{cal})^2}} \qquad (7)$$

The En ratios show that the experimentally observed phase-change correction and the calculated value are in good agreement with En number below 1.

Measurement uncertainties of gauge blocks were evaluated where the major components are summarized in equation (8).

$$\begin{aligned} u^2(l) = & \, u^2(l_{fit}) + u^2(l_t) + u^2(l_w) + u^2(l_A) \\ & + u^2(l_\Omega) + u^2(l_n) + u^2(l_G) + u^2(l_F) \\ & + u^2(l_R) + u^2(l_\Phi) \end{aligned} \qquad (8)$$

The terms listed in equation (8) represent the uncertainty components for the following influences: wavelength (l_{fit}), temperature (l_t), wringing (l_w), wavefront error (l_A), obliquity correction (l_Ω), refractive index of air (l_n), flatness and parallelism (l_G), plate bending (l_F), variation of roughness (l_R) and phase change correction (l_ϕ).

Measurement uncertainties of gauge blocks and the components of length dependent part of combined standard uncertainty are summarized in Table 4. The corresponding expression for standard uncertainty at $k = 2$ is given by

$$U_{95\%}(l) = \sqrt{(24)^2 + (0.5 \cdot L)^2} \text{ nm} \qquad (9)$$

where L is the nominal length of gauge block in millimeters.

Table 4 Components of combined standard uncertainty of gauge block calibrations.

Source of uncertainty	Contribution Uncertainty, u_i (y)
Vacuum wavelength; $u(l_{fit})$	2.41 nm
Gauge block temperature; $u(l_t)$	-
Wringing influence; $u(l_w)$	6 nm
Wavefront error; $u(l_A)$	3.46 nm
Obliquity correction; $u(l_\Omega)$	-
Refractive index of air; $u(l_n)$	-
Flatness and Parallel; $u(l_G)$	1.62 nm
Bending of plate; $u(l_F)$	5 nm
Variation of roughness; $u(l_R)$	5.77 nm
Phase change correction; $u(l_\phi)$	4.6 nm
Uncertainty, $U_{95\%}$	24 nm

4. Conclusion

The determination model presented here for determining the phase-change correction of gauge blocks has improved the state of the art for determining these corrections at a practical level. The method has many advantages. It is quick, cost effective and robust enough that measurements of all

gauge block-auxiliary plate pairs can now be compensated. Working hours needed to obtained phase-change corrections of 12 gauge block-auxiliary plate pairs by using our model is half of the time need to perform the stacking method. A disadvantage of this technique is that wringing film issue and gauge block geometry issue are still the dominant uncertainty source.

The measurement results indicate that the estimated phase-change correction using this technique is effective. Phase-change corrections obtained from the experiment and from our determination model were applied to the gauge block length compensation. All En ratios are below 1 which illustrated that the experimentally observed phase-change correction and the calculated value are in excellent agreement.

5. Acknowledgement

6. References

[1] ISO 3650: 1998 "Geometrical product specification (GPS) – Length standards – Gauge blocks" Geneva.

[2] J.E. Decker and J.R. Pekelsky; "Uncertainty evaluation for the measurement of gauge blocks by optical interferometer", Metrologia, 34, 1997, pp. 479-493.

[3] R.K. Leach and A. Hart; "EUROMET Project 413: Inter-laboratory comparison of measurements of the phase correction in the field of gauge block interferometry", 15 pages.

[4] E.G. Thwaite, "Phase correction in the interferometric measurement of end standards", Metrologia, 14, 1978, pp. 53-62.

[5] P.E. Ciddor; "Phase correction in gauge block interferometry: New procedures", CSIRO Australia, DAP Technical Memorandum, 72, 12 pages.

[6] H. Matsumoto and L. Zeng; "Simple compensation method for wringing errors in the interferometric calibration of gauge blocks", Metrologia, 33, 1996, pp. 1-4.

[7] J.E. Decker, A. Ulrich, A. Lapointe, M. Viliesid and J.R. Pekelsky, "Two-part study towards lowest uncertainty calibration of ceramic gauge blocks: interferometry and mechanical comparison techniques", Proceedings of SPIE, 4401, 2001, pp. 23-32.

[8] J.E. Decker, A. Lapointe, J. Stoup, M. Viliesid Alonso and J.R. Pekelsky; "NORAMET comparison of gauge block measurement by optical interferometry", Metrologia, 36, 1999, pp. 421-432.

[9] R.K. Leach, A. Hart, EUROMET Project 413: Inter-laboratory comparison of measurements of the phase correction in the field of gauge block interferometry.

[10] R.K. Leach, "Measurement of a correction for the phase change on reflection due to surface roughness", Proceedings of SPIE, 3477, 1998, pp. 138-151.

[11] I. Malinoysky, A. Titov, J.A. Dutra, H. Belaïdi, R.S. Fransa and C.A. Massone, "Toward subnanometer uncertainty in interferometric length measurements of short gauge blocks", Applied Optics, 38, 1999, pp. 101-112.

[12] A. Titov, I. Malinovsky, H. Belaïdi, R.S. França and C.A. Massone, "Precise Interferometric Length and Phase-Change Measurement of Gauge Blocks Based on

Reproducible Wringing," Applied Optics, 39, 2000, pp. 526-538.

[13] G. Bönsch, "Interferometric calibration of an integrating sphere for the determination of the roughness correction of gauge blocks", Proceedings of SPIE 3477, 1998, pp. 152-160.

[14] J.E. Decker, P. Franke and G. Bönsch, "On the influence of gauge block roughness characteristic and surface treatment on length calibration by optical interferometry", Proceedings of SPIE , 5879, 2005, pp. 587907-1 - 587907-7.

[15] G. Bönsch, "Gauge blocks as length standards measured by interferometry or comparison: Length definition, traceability chain and limitations", Proceedings of SPIE 3477, 1998, pp. 199-210.

[16] T. Doi, K. Toyoda and Y. Tanimura, "Effects of phase change on reflection and their wavelength dependence in optical profilometry", Applied Optics, 36, 1997, pp. 7157-7161.

[17] Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM), JCGM 100.2008 GUM 1995 with minor corrections, International Organization for Standardization, Geneva, Switzerland, 2008.

[18] M.G. Cox, "The Evaluation of Key Comparison Data", Metrologia, 39, 2002, pp. 589-595.