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Uncertainty reducing method for the reference standards in gauge block comparator calibration

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ABSTRACT

A simple method for reducing the uncertainty of reference standards has been proposed for gauge block comparator calibration. Errors due to the reference value of the length difference for mechanical comparator evaluation can be reduced by using the average of two reference values. Two reference values of length difference are obtained by the appropriate combination of three gauge blocks. Errors caused by reference gauges are canceled and averaged. An error reduction effect was successfully demonstrated using an actual mechanical comparator.

1. Introduction

Gauge blocks are commonly used for practical length standards. For the high-precision calibration requirement, the length of a gauge block is calibrated using a Michelson type interferometer. However, generally, most gauge blocks are calibrated using a mechanical gauge block comparator in which reference gauges are used. In the gauge block calibration, the length difference between a measurement gauge and a reference gauge is measured using a mechanical comparator.

For the uncertainty evaluation of the mechanical comparator, several pairs of calibrated gauge blocks, the length difference of which ranges from 0 μm to approximately 10 μm, are used as the reference standard. By comparing the length difference of the calibrated values (reference value) and the measured length difference, the uncertainty of the mechanical comparator can be estimated. Mainly, the linearity specification of mechanical comparator is evaluated.

In the usual uncertainty evaluation of the mechanical comparator, one pair of calibrated gauge blocks is used twice. Reference and measurement gauge blocks are reversed to make an opposite reference value of length difference. This simple reversal tests can apparently give a good linearity data of the mechanical comparator probe. However, the errors in the calibrated values of gauge blocks are also reversed (not canceled) in this method. Therefore, the evaluated linearity includes the error in the calibrated value of the length difference and then the absolute uncertainty of the mechanical comparator is not accurately evaluated by the linearity data obtained from the reversed test.

Needless to say, the uncertainty of the reference value of the gauge block length difference has to be incorporated into the total uncertainty [1]. Therefore, the uncertainty of the calibrated values of the gauge block pair should be as small as possible. In the previous calibration guide of the European cooperation for Accreditation of Laboratories (EAL), an expanded uncertainty ($k = 3$) of the reference value of the gauge length difference was required to be less than or equal to 0.015 μm [2]. However, there are few

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calibration laboratories in which the calibration capability for gauge length difference is better than the standard uncertainty of 5 nm. According to recently developed guidelines for gauge block comparator calibration, the reference value of the gauge length difference shall be calibrated with an expanded uncertainty ($k = 2$), preferably less than or equal to 0.02 μm [3].

In the present paper, we propose a simple method by which to reduce the uncertainty of the reference value of the gauge block length difference. By combining two pairs of calibrated gauge blocks at each length difference value, the common error can be canceled in uncertainty evaluation. In the proposed method, uncertainty of the mechanical comparator evaluation can be improved even when the uncertainties of the reference gauge blocks are not so small. In addition, proposed canceling effect can be applied when the reference values are more than three (the group standards).

2. Theory and proposed method

Fig. 1 shows a basic configuration of the gauge block comparator. The length of the measurement gauge is given as the sum of the calibrated length of the reference gauge l_s and the length difference d measured by a mechanical comparator. In order to evaluate the uncertainty of the mechanical comparator, reference standards of the gauge length difference are necessary. Generally, a calibrated gauge block pair is used and the difference in length of the blocks is measured. Difference D between the reference value R (the length difference of the calibrated values) and the measured length difference d is considered in the uncertainty evaluation.

When the calibrated gauges l_{sa} and l_{sb} are used for the uncertainty evaluation, difference D_{ab} between reference value R_{ab} (=$l_{sb}-l_{sa}$) and measured length difference d_{ab} is expressed as:

$$\begin{aligned} D_{ab} &= d_{ab} - R_{ab} = d_{ab} - (l_{sb} - l_{sa}) \\ &= (\lambda_{ab} + \varepsilon_m + \varepsilon_{rab}) - (\lambda_{ab} + \gamma_{sb} - \gamma_{sa}) \\ &= \varepsilon_m + \varepsilon_{rab} - (\gamma_{sb} - \gamma_{sa}), \end{aligned} \tag{1}$$

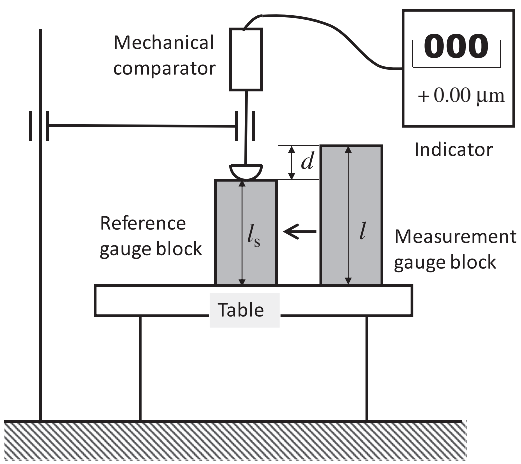

Fig. 1. Basic configuration of the gauge block comparator.

where λ_{ab} is the true value of the length difference, which is unknown, ε_m and ε_{rab} are, respectively, the systematic error and the random error of the measured length difference, which is caused by the mechanical comparator. Moreover, γ_{sa} and γ_{sb} are the errors of the calibrated values of l_{sa} and l_{sb}, respectively. As expressed in Eq. (1), difference D_{ab} is given as the error value difference between reference value R_{ab} and measured length difference d_{ab}. The second term ($\gamma_{sb}-\gamma_{sa}$) in Eq. (1) corresponds to the uncertainty due to the reference value, which should be included in total uncertainty evaluation. Theoretically, the square of the standard uncertainty $u(R_{ab})$ of the reference value is given as the expectation of $(\gamma_{sb}-\gamma_{sa})^2$, as follows:

$$u^2(R_{ab}) = E[(\gamma_{sb} - \gamma_{sa})^2] = E[\gamma_{sa}^2] + E[\gamma_{sa}^2], \tag{2}$$

where we assume that there is no correlation between γ_{sa} and γ_{sb}. The squares of the standard uncertainties of the calibrated values of l_{sa} and l_{sb} are given as the expectation of γ_{sa}^2 and $\gamma_{sb}^2 (u^2(l_{sa}) = E[\gamma_{sa}^2]$ and $u^2(l_{sb}) = E[\gamma_{sb}^2])$, respectively. Therefore, when the standard uncertainties of the calibrated values of l_{sa} and l_{sb} are equal to the calibration uncertainty of gauge block u_g, the uncertainty $u(R_{ab})$ of the reference value is estimated as follows:

$$u(R_{ab}) = \sqrt{u_g^2 + u_g^2} = \sqrt{2}u_g. \tag{3}$$

The standard uncertainty $u(R_{ab})$ of the reference value for the evaluation of the mechanical comparator becomes $\sqrt{2}$ times larger than that of the single gauge block. Normally, calibrated gauge blocks of approximately 1 mm in length are used to make reference standard. Generally, the standard uncertainty of the 1-mm gauge calibrated by an interferometer is approximately 10–15 nm. Therefore, the standard uncertainty $u(R_{ab})$ is estimated to be approximately 15–20 nm. To achieve the standard uncertainty of 10 nm for $u(R_{ab})$ requires a special calibration method for the gauge length difference.

In the present study, for reducing the uncertainty of the reference standard, we propose a simple method in which an additional gauge block pair (reference standard) is added. When the additional reference standard is constructed of calibrated gauges l_{sb} and l_{sc}, difference D_{bc} between reference value R_{bc} (=$l_{sc}-l_{sb}$) and measured length difference d_{bc} is given as follows:

$$D_{bc} = d_{bc} - R_{bc} = \varepsilon_m + \varepsilon_{rbc} - (\gamma_{sc} - \gamma_{sb}), \tag{4}$$

where the value of R_{bc} is approximately equal to R_{ab} ($R_{ab} \fallingdotseq R_{bc}$). The systematic error ε_m of the measured length difference in D_{bc} is approximated to be equal to that in D_{ab}, because the values of the length differences are approximately the same. Fig. 2 shows an example of the gauge block combination of the proposed method. In the first pair of reference standards, the gauge l_{sa} is set as the reference gauge, and the gauge l_{sb} is set as the measurement gauge. In the second pair of reference standards, the gauge l_{sb} is set as the reference gauge, and the gauge l_{sc} is set as the measurement gauge. A total of three calibrated gauge blocks are used.

From Eqs. (1) and (4), the average D_{ave} of D_{ab} and D_{bc} is calculated as follows: