Characteristics of Linear Variable Differential Transformer (LVDT) Probe for Gauge Blocks Calibration

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Abstract. The LVDT probe is a very important component used in gauge blocks calibration via a mechanical comparative method. The probe is used to determine the central length difference between a reference gauge block and gauge block under-tested (UTC). Typically, an UTC and a reference gauge block have the same nominal length. However, some gauge blocks UTC are specially made for specific purpose where the reference gauge blocks with the same nominal length are not commercially available. Various reference gauge blocks are wrung in order to provide nominal length the same as that of the UTC. Wringing process is the troublesome step and causes larger measurement uncertainty. The lower accuracy is higher number of gauge block used to create reference gauge block, in order to improve accuracy of measurement, the LVDT probe was used at the longer range where the reference gauge block and the UTC don’t need to be the same nominal length. In this paper, characteristics of LVDT probe was investigated as it is related to the accuracy of the measurement result. Errors of LVDT probe came from non-linearity, calibration factor, retrace error, repeatability and maximum difference in length. A pair of gauge block, calculated by the Twyman-Green interferometer, length different range 5 μm to 230 μm was used in the study. Non-linearity of LVDT is evaluated by a simple linear regression model. The non-linearity of LVDT probe, calibration factor, retrace error, repeatability and maximum difference in length are 25 nm, 1.0003, 3 nm, 6 nm and 80 nm, respectively. Therefore, by using this technique, central length difference between the 2 gauge blocks up to 80 nm can be calibrated with the uncertainty due to non-linearity of 15 nm The experiment shows the large error of retrace closes to 0.02 μm at 0.09 μm. This can be determined the maximum difference in length to calibrate gauge blocks at difference nominal lengths. The measurement uncertainty of non-linearity is evaluated and it is close to 15 nm.

1. Introduction

Gauge block is used to calibrate dimensional measuring instrument such as micrometer, vernier caliper, coordinate measuring machine (CMM) and universal length machine (ULM) because it is easy to use and with high accuracy. Gauge block calibration generally follows the standard ISO3650:1998 [1] which is using mechanical comparison method. In order to determine length of an unknown gauge block, the difference of its central length from that of the reference gauge block shall be measured. After applying algebraically to the actual length of the reference gauge block, true length of an unknown gauge block can be determined. For probing, the measuring faces of each gauge are approached from opposite
directions and length difference is measured by a high resolution indicator in the gauge block comparator system.

2. Measurement principle

2.1. Central length measurement
The calibration of gauge block is carried out by comparison using comparator and a calibrated gauge block of the same nominal length and the same material as reference standard as show in figure 1.

\[
V_{CD} = x \left( l_s \alpha_s \Delta t - l_x \right) + \delta x + \delta L - L \left( \alpha_x \times \Delta t + \delta \alpha \times \Delta t \right)
\]

Where;
- \( l_s \) is length of the reference gauge block at the reference temperature to \( t = 20 \) °C according to its calibration certificate,
- \( \Delta l_D \) is change of the length of the reference gauge block since its last calibration due to drift,
- \( \Delta l_c \) is correction for non-linearity and offset of the comparator,
- \( L \) is nominal length of the gauge blocks considered,
- \( \alpha_s = (\alpha_s + \alpha_r) / 2 \) is average of the thermal expansion coefficients of the unknown and reference gauge blocks,
- \( \Delta t = t_s - t_x \) is temperature difference between the unknown and reference gauge blocks,
- \( \delta \alpha = \alpha_x - \alpha_s \) is difference in the thermal expansion coefficients between the unknown and the reference gauge blocks,
- \( \Delta t = (t_s + t_x) / 2 - t_0 \) is deviation of the average temperature of the unknown and the reference gauge blocks from the reference temperature and \( \delta l_x \) is correction for non-central contacting of the measuring faces of the unknown gauge block.

![Figure 1. Schematic diagram of gauge block calibration](image-url)
2.2. Non-linearity measurement and calibration factor of LVDT

Correction for non-linearity of LVDT probes in equation (1) is main error sources when unknown and reference gauge blocks are difference nominal length. Length different of a pair of gauge block calculated by the Twyman-Green interferometer ($l_c$) was compared with length different measuring by the comparator ($l_m$) for non-linearity measurement. Non-linearity of LVDT probes is evaluated by a simple linear regression model [3].

\[ l_{CM} = k_0 + k_1 l_C \]  

Where; $l_{CM} = l_c - l_m$, $k_0 = \overline{l}_{CM} - k_1 \overline{l}_C$ and $k_1 = \frac{\sum (l_{C,j} - \overline{l}_C) (l_{CM,j} - \overline{l}_{CM})}{\sum (l_{C,j} - \overline{l}_C)^2}$

Non-linearity correction of LVDT probes was calculated by $\delta C = (l_{CM,max} - l_{CM,min})/2$, uncertainty due to non-linearity was calculated by $u(\delta C) = \delta C / \sqrt{3}$ [4] and calibration factor ($C$) was determined by the ratio between length different calculated by the Twyman-Green interferometer ($l_c$) and length different measuring by the comparator ($l_m$).

3. Preliminary experiment and discussion

The experiment was carried out on dual probes gauge block comparator (GBC) manufacturer by Mahr, Model 826 PC. Schematic diagram of the GBC is illustrated in figure 2. GBC consist of a high resolution display unit, upper probe and lower probe made of tungsten carbide with ball the diameter of 3 mm and measuring force of dual 0.75 N and temperature compensation unit manufacturer by Albhorn, Model 2390-8.

![Figure 2. Experimental setup](image)

A pair of gauge block made of steel manufacturer by Mitutoyo, calculated by the Twyman-Green interferometer, length different rage 5 \(\mu\)m to 230 \(\mu\)m was used in the study. Table 1 show the measurement results of LVDT probes.

| $l_c$ (\(\mu\)m) | $l_m$ (\(\mu\)m) | $l_{CM}$ (\(\mu\)m) | $C$ |
|------------------|------------------|-------------------|-----|
| -230.036 / 230.036 | -229.847 / 229.870 | -0.189 / 0.166 | 1.0008 / 1.0007 |
| -200.022 / 200.022 | -199.873 / 199.883 | -0.149 / 0.139 | 1.0007 / 1.0007 |

Table 1. Measurement results of LVDT probes
| $l_c$ ($\mu$m) | $l_t$ ($\mu$m) | $l_m$ ($\mu$m) | $C$ |
|-------------|-------------|-------------|-----|
| -180.053 / 180.053 | -179.920 / 179.923 | -0.133 / 0.130 | 1.0007 / 1.0007 |
| -100.023 / 100.023 | -99.963 / 99.967 | -0.060 / 0.056 | 1.0006 / 1.0006 |
| -90.063 / 90.063 | -89.983 / 90.003 | -0.080 / 0.060 | 1.0009 / 1.0007 |
| -80.010 / 80.010 | -79.983 / 79.987 | -0.027 / 0.023 | 1.0003 / 1.0003 |
| -70.007 / 70.007 | -69.983 / 69.990 | -0.024 / 0.017 | 1.0003 / 1.0002 |
| -60.001 / 60.001 | -59.977 / 59.983 | -0.024 / 0.018 | 1.0004 / 1.0003 |
| -50.024 / 50.024 | -50.000 / 50.003 | -0.024 / 0.021 | 1.0005 / 1.0004 |
| -39.990 / 39.990 | -39.980 / 39.990 | -0.010 / 0.000 | 1.0003 / 1.0000 |
| -30.049 / 30.049 | -30.030 / 30.037 | -0.019 / 0.012 | 1.0006 / 1.0004 |
| -20.038 / 20.038 | -20.037 / 20.043 | -0.001 / -0.005 | 1.0001 / 0.9997 |
| -9.909 / 9.909 | -9.907 / 9.910 | -0.002 / -0.001 | 1.0002 / 0.9999 |
| -4.784 / 4.784 | -4.783 / 4.783 | -0.001 / 0.001 | 1.0001 / 1.0001 |

**Figure 3.** Non-linearity of LVDT probes

The non-linearity of LVDT probe in figure 3, calibration factor, retrace error, repeatability and maximum difference in length are 25 nm, 1.0003, 3 nm, 6 nm and 80 nm respectively. Therefore, by using this technique, central length difference between two gauge blocks up to 80 nm can be calibrated with the uncertainty due to non-linearity of 15 nm. The experiment shows large error of retrace closes to 0.02 $\mu$m at 0.09 $\mu$m. This can be determined the maximum difference in length to calibrate gauge block at difference nominal length.

**4. References**

[1] International Organization for Standardization 1998 *ISO 3650 Geometrical Product Specifications (GPS) – Length Standards – Gauge Blocks* Second edition 11-12

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