Measurement optimization of high accuracy check master based on interferometry method in National Standardization Agency of Indonesia: a preliminary study for measuring range of 10 mm to 400 mm

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Abstract. High accuracy check master is a type of geometry gauge that often used to check the accuracy of Coordinate Measuring Machine (CMM) in the high-class metrological institutes and manufacturing industries. This type of geometry gauge is composed of several high-accuracy short gauge blocks and a large rod as its foundation. Conventionally, the measurement of high accuracy check master can be carried on by using measuring machine. Since the bench has limit up to 400 mm, the measurement of high accuracy check master more than 400 mm range is performed in two-step. Firstly, from nominal range of 10 mm to 400 mm and the other range by utilizing extension. In some cases, this measurement method has bigger expanded uncertainty value, i.e. more than 2 µm. Since the check master has important role to verify the accuracy of CMM, the quality of calibration system of high accuracy check master is required to be improved. This paper describes only to achieve high accuracy of measurement up to 400 mm. In the developed measuring system, the heterodyne laser interferometer is used as the reference. The optical configuration of laser is combined with the measuring machine as a moving part. In order to improve the accuracy of measurement, the refractive index of air and the temperature compensation are recalculated manually by Edlen’s formula and linear expansion equation, respectively. Using this method, the expanded uncertainty from calibration 400 mm high accuracy check master is less than 1 µm. The results had a good agreement to the measurement results from manufacturer with international certification, experimentally. In conclusion, this method can be applied to calibrate the high accuracy check master of 400 mm range.

1. Introduction

CMM is an instrument used to measure three-dimensional coordinates of measuring object, both using contact and non-contact methods. This measuring instrument is widely used by high-class metrological institutes and manufacturing industries, e.g. to measure hole of diameters, blade angle of the wind turbine, frame dimension of vehicle, alignment of shafts on battle tank wheels, and other measurement purposes. Technically, the CMM performance test is referring to ISO 10360. The ISO 10360 method basically tests several dimensional parameters, e.g. the accuracy of reading scale on each of x, y, and z axis; perpendicularity between x-y, y-z, and x-z axis pairs; straightness of each x, y, and z-axis; and rotational errors (roll, pitch, and yaw) on each x, y, and z-axis. Check master (commonly also known as
step gauge) is one type of geometry gauge that often used to check CMM accuracy. This type of geometry gauge consists of several high-accuracy short gauge blocks and a large rod as its foundation. Some of the National Metrology Institutes (NMIs) have developed a different type of check master calibration system. Korea Research Institute of Standards and Science (KRISS) has developed a measurement system for calibration of a check master and a line standard with a multi-axis laser interferometer for direct metrological traceability and active compensation of angular motion errors [1]. These systems can calibrate a check master and a line standard by changing probes (contact and optical probe). National Metrology Institute of Japan (NMIJ) uses CMM with laser interferometer to calibrate the check master [2]. National Metrology Institute of Finland MIKES developed an interferometric step gauge for CMM verification [3]. MIKES also developed a high accuracy check master calibration system with four laser interferometers [4]. National Institute of Standards and Technology (NIST) has developed a check master calibration device using a specially designed induction type probe [5]. NIST measurement system has similarities with NMIJ, which is based on the CMM measurement. National Institute of Metrology (NIM) has developed a computational model to realize the high precision calibration of the step gauge based on combination between the commercial CMM and laser interference technology [6]. In general, the check master calibration systems of some National Metrology Institutes are based on a combination between contact probe and laser interferometer method.

The measuring machine, namely SIP 414M machine, is one of the standards used for length measurements at the National Standardization Agency of Indonesia [7]. The machine can be used to calibrate check master, caliper checker, and line standard [8] with a measurement uncertainty value of more than 2 μm. This value is the optimal result that can be achieved by using SIP 414M machine due to the uncertainty contribution of its standard and resolution of 40%, respectively. Since the check master has important role to verify the accuracy of CMM, the quality of calibration system of high accuracy check master is required to be improved.

This paper discussed the calibration of a high accuracy check master based on the interferometer method and its uncertainty evaluation. This calibration method used a high accuracy check master from Mitutoyo, the heterodyne laser interferometer from Agilent Technology, and the measuring machine from Societe Genevoise D' Instruments De Physique (SIP) as moving part. This paper describes only to achieve high accuracy of measurement up to 400 mm. In order to improve the accuracy of measurement, the refractive index of air and the temperature compensation are recalculated manually by Edlen’s formula [9] and linear expansion equation [10], respectively. This analysis is separate from the manufacturer's laser interferometer software due to the manufacturer's system does not have an error mapping facility to compensate errors from the reading of temperature, pressure and humidity sensors properly.

The purpose of this research is to develop a measurement system for high accuracy check master in Indonesia. The results of this experiment are preliminary data to carry on an international comparison, as one of the requirements to obtain the international recognition of measurement capabilities in Appendix C on International Bureau of Weights and Measures (BIPM).

2. Research Methodology
This research was carried in length laboratory with a room temperature of (20.28 ± 0.07) °C and relative humidity of (54.07 ± 0.60) %. This research used a wavelength of laser interferometer and some sensors of temperature, pressure, and humidity. The laser interferometer and all of the sensors are traceable to the International System of Units (SI) through National Measurement Standards Laboratory, SNSU-BSN, Indonesia [11,12,13]. The unit under test of this research is a high accuracy check master from Mitutoyo with measuring range of 10 mm to 600 mm. Since the bench has limit up to 400 mm, the measurement of the high accuracy check master is performed by length of 400 mm only. The Experimental scheme of this research is shown in Figure 1.
Figure 1. Experimental set-up.

In order to determine the value of calibrated length at 20 °C, the refractive index of air and the temperature compensation needs to be recalculated. The calculation of the refractive index of air can be approximated by using Edlen's formula as described below:

\[(n - 1) \times 10^5 = f(\lambda_0) \cdot f(p,t) - f(R,t,\lambda_0)\]  \hspace{1cm} (1)

where

\[f(\lambda_0) = 8342.54 + \frac{2406147}{130 - \lambda_0^2} + \frac{15998}{38.9 - \lambda_0^2}\]  \hspace{1cm} (2)

\[f(p,t) = \frac{p}{96095.43} \left(1 + 10^8 \left(0.601 - 0.00972t\right)p\right)\]  \hspace{1cm} (3)

\[f(R,t,\lambda_0) = R(8.753 + 0.036588t^2) \left(0.0373345 - \frac{0.000401}{\lambda_0^2}\right)\]  \hspace{1cm} (4)

with \(n\) = refractive index of air, \(\lambda_0\) = wavelength in vacuum (\(\mu\)m), \(t\) = temperature of air (°C), \(p\) = air pressure (Pa), \(R\) = humidity (%)

While the temperature compensation due to thermal expansion of the gauge block and check master can be approximated by the linear expansion equation which is formulated by equation (5). The temperature compensation is a method to adjust a measurement system to compensate for the effects caused by changes in temperature.

\[\frac{\Delta l}{l_0} = \alpha_t \times \Delta T\]  \hspace{1cm} (5)

with \(\Delta l\) = change in length (mm), \(l_0\) = original length (mm), \(\alpha_t\) = linear coefficient of thermal expansion (K^{-1}), \(\Delta T\) = change in temperature (K).

The calibration of probe offset is carried on by using a gauge block reference of 50 mm. The purpose of this calibration step is to determine the probe correction value. The length standard is determined by the value of calibrated length at 20 °C and probe correction.
3. Result and Discussion

3.1. Uncertainty evaluation

The calibration value of high accuracy check master is obtained by equation (6).

\[ L = l_{opt} + \Delta T_{20} \cdot \alpha \cdot l + \Delta l_c + \Delta l_\epsilon + \delta l_m \] (6)

where

\[ l_{opt} = \frac{\lambda_0}{2n} (m + \varepsilon) \] (7)

The uncertainty of high accuracy check master calibration is calculated by the equation (8).

\[ u^2(L) = \left[ \frac{u(L)}{\lambda_0} \right]^2 l_{opt}^2 + \left[ \frac{u(n)}{n} \right]^2 l_{opt}^2 + \left[ \frac{u(\varepsilon)}{2} \right]^2 u^2(\varepsilon) + \alpha^2 \cdot L^2 \cdot u_\beta^2 + \Delta T_{20}^2 \cdot L^2 \cdot u_\delta^2 + u^2(\Delta l_c) + u^2(\Delta l_\epsilon) + u^2(\delta l_m) \] (8)

where \( L \) = nominal length of high accuracy check master, \( l_{opt} \) = optically measured length, \( u(L) \) = uncertainty of high accuracy check master calibration based on laser interferometer, \( u(\lambda_0) \) = uncertainty of wavelength in vacuum, \( u(n) \) = uncertainty refractive index of air, \( u(\varepsilon) \) = uncertainty of phase measurement, \( u_\beta = \) uncertainty of check master temperature measurement, \( u_\delta \) = uncertainty of thermal expansion coefficient, \( u(\Delta l_c) \) = uncertainty of alignment error (cosine error), \( u(\Delta l_\epsilon) \) = uncertainty of abbe error (sine error), \( u(\delta l_m) \) = uncertainty of check master measurement.

The tabulation of measurement uncertainty budget of high accuracy check master calibration based on laser interferometer is shown in Table 1.

| Item                                | Value                  | Factor | uncertainty at \( L = 400 \text{ mm} \) |
|-------------------------------------|------------------------|--------|------------------------------------------|
| Laser interferometer                |                        |        |                                          |
| Wavelength                          | \( 16 \times 10^{-9} \) | L      | \( 0.0064 \mu\text{m} \)                |
| Resolution                          | \( 10 \text{ nm} \)    | 1      | \( 0.01 \mu\text{m} \)                  |
| Alignment (cosine error)            | \( 0.8 \text{ mrad} \) | 0.35 x \( 10^{-6} \) | \( 0.14 \mu\text{m} \)                  |
| Abbe error                          | \( 50 \text{ mm, 1.1 arcsec} \) | -     | \( 0.27 \mu\text{m} \)                  |
| Refractive index of air              |                        |        |                                          |
| Pressure                            | \( 1 \text{ hPa} \)    | \( 0.27 \times 10^{-6} \) | \( 0.108 \mu\text{m} \)                |
| Temperature                         | \( 0.5 \text{ °C} \)   | \( 0.5 \times 10^{-6} \) | \( 0.2 \mu\text{m} \)                  |
| Humidity                            | \( 0.6 \% \)          | \( 0.05 \times 10^{-6} \) | \( 0.02 \mu\text{m} \)                  |
| Check master thermal expansion      |                        |        |                                          |
| Temperature                         | \( 0.06 \text{ °C (11.5 ppm)} \) | \( 0.69 \times 10^{-6} \) | \( 0.276 \mu\text{m} \)                |
| Coefficient of thermal expansion    | \( 0.1 \text{ ppm (0.17 °C) } \) | \( 0.017 \times 10^{-6} \) | \( 0.0068 \mu\text{m} \)                |
| Check master setting                |                        |        |                                          |
| Alignment (cosine error)            | \( 0.5 \text{ mrad} \) | \( 0.125 \times 10^{-6} \) | \( 0.05 \mu\text{m} \)                  |
| Face detection                      | Uniformity of probe deflection | 0.1 µm | \( 0.1 \mu\text{m} \)                  |
| Standard uncertainty                |                        |        | \( 0.48 \mu\text{m} \)                  |
| Expanded Uncertainty (k=2)          |                        |        | \( 0.97 \mu\text{m} \)                  |

3.2. Calibration result

The calibration results of high accuracy check master are shown in Figure 2. Figure 2 (a) shows the distribution of 3 (three) samples of measurement results. Each sample of measurement result shows the fluctuation of values due to random error. The random errors can be caused by some factors, e.g.
temperature fluctuations, vibrations, instrument characteristics, etc. In order to reduce this error, the three samples of measurement results have been averaged as shown in Figure 2 (b). Although the results are not so smooth but it had a good agreement to the measurement results from manufacturer with international certification. According to the technical data from manufacturer, the block pitch accuracy of check master is ±1.2 μm for measuring range of 0 mm to 310 mm and ±1.8 μm for measuring range of 310 mm to 400 mm. It means that generally all measurement results are within the range specification and acceptable, although some points look to approaching the lower limit line.

![Figure 2](image-url)  
*Figure 2. Calibration results of high accuracy check master based on laser interferometer*

In this research, the largest contribution of random error is suspected due to temperature fluctuations and mechanical backlash from the SIP 414M machine as a moving part. In order to make uniform conditions, two thermo-hygrometer sensors are used to measure room temperature and placed in some different positions. However, during the experiment, temperature fluctuation was an unpredictable factor due to the air conditioning system in the laboratory. Meanwhile, the mechanical backlash in the SIP 414M machine cannot be avoided because this machine uses the gear as its driving system (transmission) [14].

4. Conclusion

Preliminary study for measuring of a high accuracy check master based on a laser interferometer in SNSU-BSN has been conducted and the results have been analysed and compared with the measurement results of the manufacturer. Using this method, the expanded uncertainty of less than 1 μm is obtained from calibration of high accuracy check master with measuring range of 10 mm to 400 mm. It means that this method is acceptable, experimentally. In the next development of high accuracy check master calibration based on laser Interferometer in SNSU-BSN, the biggest challenge come from the design of measurement systems and environmental conditions. A measurement system design that does not meet the Abbe principle will be difficult to reduce the measurement uncertainty value. The same thing also applies to environmental conditions with unstable temperature.

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