

CALIBRATION OF INVAR ANGULAR INTERFEROMETER OPTICS WITH MULTI-STEP METHOD

Yao Huang¹, Zi Xue¹ and He Yan Wang²

¹ National Institute of Metrology, China, No.18, Bei San Huan Dong Lu, Beijing 100029, P.R.China, huangyao@nim.ac.cn

Abstract:

In National Institute of Metrology, China (NIM), the Small Angle Measuring System which is based on sine principle, is developed as the national primary standard for the plane angle in the angular measuring range $\pm 5^\circ$. The measurement uncertainty of this system is dominated by the accuracy of an Invar Angular Interferometer Optics. To calibrate this Invar Interferometer system, a series of known reference standards were given with multi-step method using a double-deck rotary table. The calibration got an uncertainty lower than 0.03 arcsec ($k=2$).

Keywords: Calibration, Angle Measuring, Invar Angular Interferometer Optics, Multi-step Method

1. INTRODUCTION

In National Institute of Metrology, China (NIM), the plane angler primary standard system consists of three sub-systems. They are ‘Index Table National Standard’, ‘Line Angle National Standard’, and ‘Laser Small Angle National Standard’.

The ‘Laser Small Angle National Standard’ was established for maintain and disseminate the angular standard quantity value in the measuring range $\pm 5^\circ$. Generally, it is used for calibration of high-resolution electronic autocollimators.

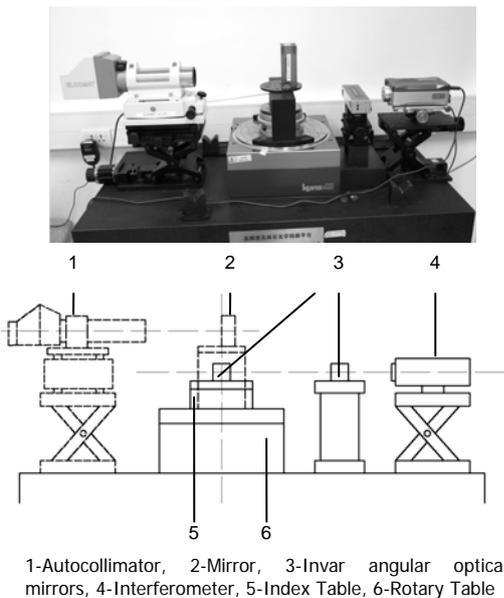


Fig. 1: Laser Small Angle National Standard in Calibration of Autocollimator

As it is shown in the figure 1, this system is developed from the small angle measuring system (developed by RENISHAW), which is based on sine principle, using concept ‘ratio of two lengths’, and equipped with interferometer.

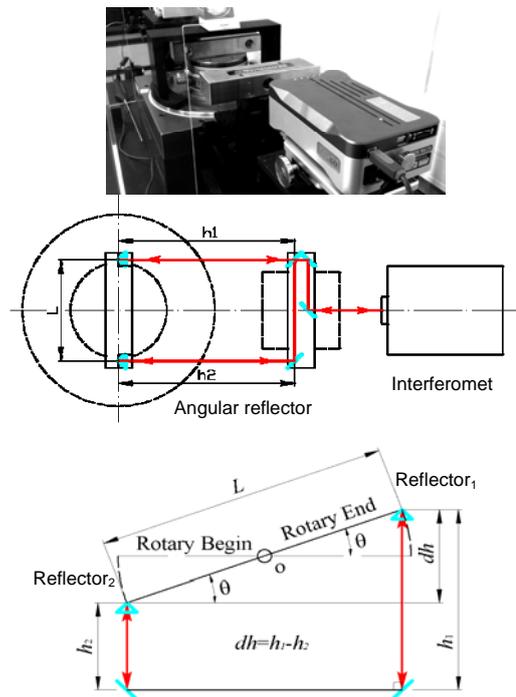


Fig. 2: Small Angle Measuring System

Figure 2 shows that the angle θ could be obtained by measuring the separation of the retro-reflectors in the angular reflector and the optical path difference between h_1 and h_2 . The model equation is:

$$\theta = \arcsin\left(\frac{dh}{L}\right) \quad (1)$$

In practical measurements, dh is the interferometer readings, acquired in the ‘Linear Measurement mode’, and the h_1 and h_2 which is absolute optical path length could not be measured. So the ‘Rotary Begin’ position could not be set where $dh=0$ directly.

As it is shown in figure 3, the model equation become:

$$\theta' = \arcsin\left(\frac{dh' + dh_0}{L}\right) - \theta_0 \quad (2)$$

Where dh' is the raw linear measurement with angular displacement θ' , dh_0 is the ‘Datum’ reading offset, L is the separation of the retro-reflectors in the angular reflector, θ_0 is the ‘Datum’ offset angle.

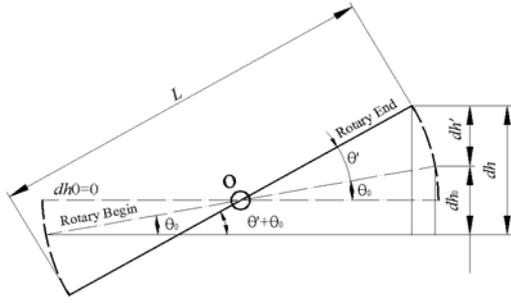


Fig. 3: Practical Measurement of Small Angle Measuring System

2. ACCURACY OF THE SYSTEM

2.1 The Application of the Approximation Equation

The equation (2) shows that dh' , L , dh_0 , and θ_0 determine the angle measurement result θ' .

Figure 3 show that, dh_0 could be gotten from θ_0 and L .

$$dh_0 = L \cdot \sin(\theta_0) \quad (3)$$

In general, θ_0 could not be measured directly, and become a measurement uncertainty contributor. The system could be adjusted to make θ_0 small enough (within $\pm 1''$) and equation (1) would be applied as an approximation equation.

The equation (1), (2), and (3), could be used to estimate the deviation come from the application of approximation equation.

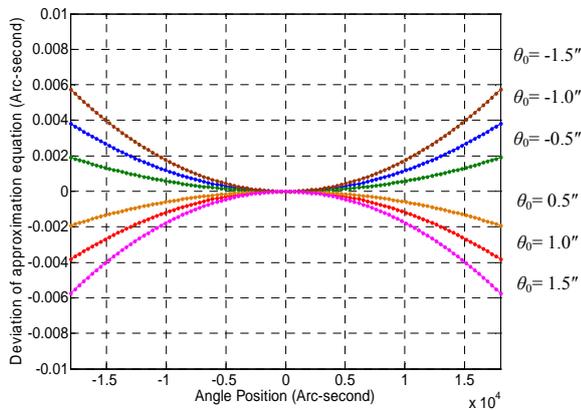


Fig. 4: The estimation of deviation comes from the application of approximation equation with different θ_0

Figure 4 show that, when the θ_0 is within $\pm 1''$, the max deviation would within $\pm 0.005''$ among the measuring range $\pm 18000''$ ($\pm 5^\circ$)

2.2 Determination of the retro-reflectors separation

The separation of retro-reflectors (L) could not be measured directly as well as the dh_0 . In small angle measuring range ($\pm 5^\circ$), the function relation of interferometer reading (dh) and angle (θ) could be approximately regarded as linear relation. So the 'Invar Angular Interferometer Optics' developer RENISHAW provide a method to determine it as the gradient of a best-fit straight line. That best-fit straight line is calculated from a series of known angle (θ) and their corresponding interferometer reading (dh).

The known angle (θ) which is generated by a normal rotary table has an accuracy of around $1.4''$. It makes the uncertainty contributed by separation of retro-reflectors worse than $1.4''$. This accuracy could not support the small angle measuring system to calibrate the autocollimator with accuracy better than $1.0''$.

The unique double deck structure of NIM's small angle measuring system shown in figure 1 allows the application of multi-step method of angle measurement.

The multi-step method of angle measurement takes advantage of the nature angle standard 360° of one full circle of any rotary table. The figure 5 shows that, if one circle of an index table could be measured by 12 divisions which is end to end. The sum of 12 divisions' angle would be error free 360° .

$$\sum_{i=1}^{12} \theta_i = 360^\circ \quad (4)$$

And an ideal 30° could be also obtained by:

$$\theta_{30^\circ} = \frac{\sum_{i=1}^{12} \theta_i}{12} \quad (5)$$

Index Table

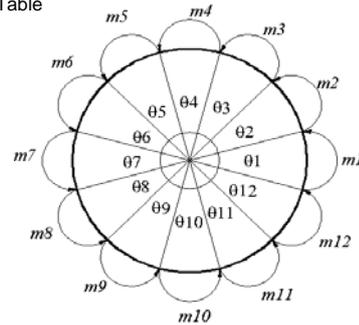


Fig. 5: The measuring principle of multi-step method

In practical measurements, one circle of the rotary table could be divided into n divisions, and a series of ideal angle could be obtained by multi-step method.

$$\theta_{\Delta} = \frac{\sum_{i=1}^n \theta_i}{n} \quad (6)$$

Where θ_{Δ} is the nominal dividing angle, θ_i is the angle of every division, i is the serial number of each division, and n is the dividing number.

Table 1: Ideal angle obtained by multi-step method with different dividing number (n)

Dividing Number (n)	Angle
72	5°
90	4°
120	3°
180	2°
360	1°

In NIM's small angle measuring system, the index table is placed on another rotary table with eccentricity error less than $5\mu\text{m}$ and the angular reflector are placed on the index table. The rotary table at the bottom could rotate with a step as same as dividing angle and in opposite rotary direction of index table every time when the interferometer finishes one

division's measurement (measuring result $m_i, i=1, 2, 3 \dots n$). In this way the small angle measuring system could measure every division's angle one by one, and get the measuring result m_{Δ} .

$$m_{\Delta} = \frac{\sum_{i=1}^n m_i}{n} \quad (7)$$

In this way, the separation of the retro-reflector (L) in angular reflector of NIM's small angle measuring system was re-calibrated with a series of known angle ($-5^{\circ}, -3^{\circ}, -1^{\circ}, 0^{\circ}, 1^{\circ}, 3^{\circ}, 5^{\circ}$) which are generated by multi-step method with uncertainty lower than $0.03''$.

As it is shown in figure 6, the measuring results were a series of interferometer reading ($m_{-5^{\circ}}, m_{-3^{\circ}}, m_{-1^{\circ}}, m_{0^{\circ}}, m_{1^{\circ}}, m_{3^{\circ}}, m_{5^{\circ}}$). The retro-reflectors separation (L) could be calculated by the linear regression of the interferometer reading ($m_{\Delta}=dh$) and their corresponding angle ($\theta_{\Delta}=\theta$), according to equation (1).

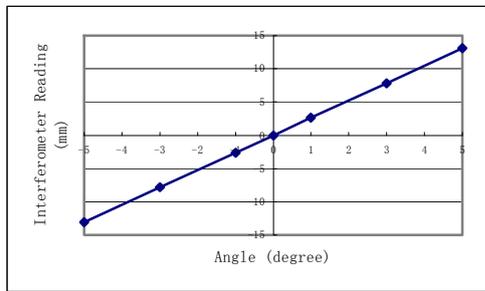


Fig. 6: Linear regression of interferometer reading and their corresponding angle

The uncertainty contributed by the determination of retro-reflectors separation is $0.03''$ with multi-step method. This makes the measuring uncertainty of NIM's small angle measuring system lower than $0.07''$.

3. COMPERISON WITH SELF-CALIBRATION ANGULAR COMPARATOR

Angle interferometer using concept 'ratio of two lengths' and angle encoder using concept 'subdivision of full circle ($2\pi \text{ rad}=360^{\circ}$)' are alternative devices for realization of SI unit radian (rad) in small angle measurement range.

NIM imported a self-calibration angular comparator with measuring uncertainty of $0.1''$. So two kinds of devices are set up in the mean time and they have similar uncertainty in small angle measuring range. A comparison between angle interferometer and angle encoder was carried out through a calibration of autocollimator.

Figure 7 show that the maximum differences between the error curves of the two systems is $0.06''$ which is lower than the measuring uncertainty of each angle measuring system. The comparison could prove the correction of each system.

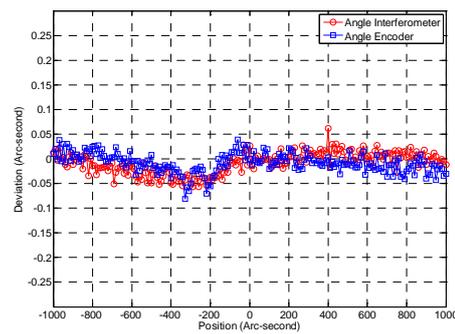


Fig. 7: Comparison between the error curves of autocollimator calibrated by angle interferometer and angle encoder

4. CONCLUSION

The small angle measuring system in NIM was re-calibrated by precision indirect measurement of the separation of retro-reflectors with multi-step method.

The uncertainty contributed by the determination of retro-reflectors separation is $0.03''$, and the whole system's measuring uncertainty is lower than $0.07''$.

A comparison between the small angle measuring system (Angular Interferometer) and the self-calibration angular comparator was carried out through a calibration of an autocollimator. The comparison proved each system's correction very well.

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