Self-calibratable rotary Table for angular Standards

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KEYWORDS : self-calibration, rotary encoder, autocollimator, polygon mirror, angular standard

SelfA (Self-calibratable Angle device) rotary encoder can detect some kinds of angle error, not only its encoder scale error, but also the encoder attachment error (eccentricity error). When rotary table with built-in SelfA encoder rotates only one revolution, inner SelfA rotary encoder can calibrate itself with a high accuracy and make this rotary table to be a calibration system for many types of angle devices. The SelfA mechanism is very simple that several number of sensor heads are arranged around one scale disc at same angle interval. In this paper, we propose the phase shift method in order to improve the performance of self-calibration function and introduce the angular calibration results of rotary encoder and autocollimator with 0.1" or more high accuracy.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

1. Introduction

We have developed the rotary table with built-in SelfA encoder [1] [2] as a simple angular standard instrument for small and medium-sized enterprises. This accuracy was about 0.3".However NMIs (National Metrology Institute) in the world have developed different type of angular calibration system for national standard respectively to calibrate various kinds of angle equipment. For example, an index table is developed for polygon mirror calibration, a small angle generator using an angle interferometer is developed for autocollimator calibration, and sin bar is used in order to calibrate levels. Therefore NMIs have a lot of calibration system as for angular standards. In order to improve the precision of the SelfA rotary table and make it the level which can be used as national angular standard which accuracy is 0.1", we develop the multi-array SelfA encoder and the phase shift combination method. In this paper, we explain these improving technic and the calibration results of rotary encoder and autocollimator to be calibrated.

2. Multi Combination SelfA encoder

2.1 Principle of Multi-Combination SelfA encoder

SelfA encoder has several number of sensor heads which are arranged around one scale disc at same angle interval as shown in Figure 1. One arbitrary sensor head is chosen as a main head A_1. While rotating one round revolution, comparison measurement of the angular signal difference $\delta_{i,(1,j)}$ between the main head A_1 and other heads A_j output is carried out. Where, i (i = 1, 2, ···, N_G) represent a graduation line number, N_G is the total graduation number of a rotary encoder, j (j = 1, 2, ···, N_H) is a reading head number and N_H is the total number of reading heads.

When the angle deviation of i-th graduation position from an ideal graduation position represents a_i, and the main reading head detects the i-th position, then the j-th head detects the graduation position of the $i+(j-1)N_G/N_H$ at same time. Therefore, the signal difference $\delta_{i,(1,j)}$ is written as follows:

$$\delta_{i,(1,j)} = a_i - a_{i+(j-1)N_G/N_H} \quad . \tag{1}$$

The difference $\delta_{i,(1,j)}$ is calculated to each sensor head j, and mean value μ_i is calculated further. It is expressed with the following formula,

$$\mu_i = \frac{1}{N_H}\sum_{j=1}^{N_H}\delta_{i,(1,j)} = a_i - \frac{1}{N_H}\sum_{j=1}^{N_H} a_{i+(j-1)N_G/N_H} \quad . \tag{2}$$

Here, we use the law of the Fourier series written in the following that can be mathematically proved about arbitrary periodic curve,

> "An arbitrary periodic curve of 2π can be expressed by the Fourier series, and when n-number of curves with a phase shift of 2π/n at a time are averaged, the averaged curve shows the sum of an integral multiple of n-order Fourier components of the original curve".

According to this law, the mean value μ_i represents the calibration curve of rotary encoder, however it does not include N_H -th order Fourier components corresponding to 2nd term of right side in eq.2.

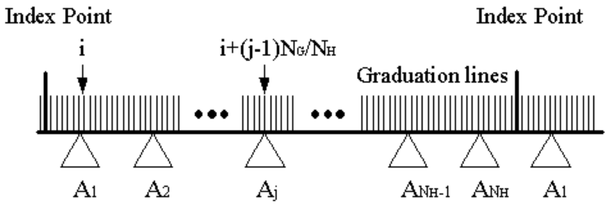

Fig. 1 Position relation between a rotary encoder scale and reading heads of self-calibratable rotary encoder.

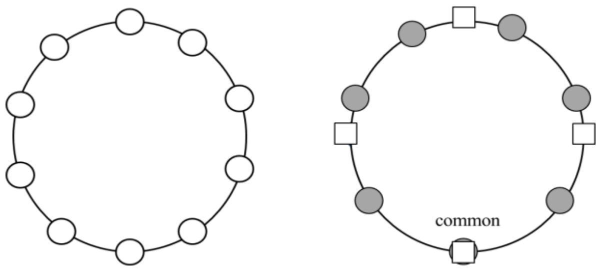

Fig. 2 Left side figure show the N_H =10 SelfA set up, the open circle indicates sensor heads position around scale disc. Right side is N_H =7 and 4 Multi Combination SelfA set up, first set is the black circle and 2nd set is the open square which indicate N_H =7 and N_H =4 SelfA sensor heads position respectively.

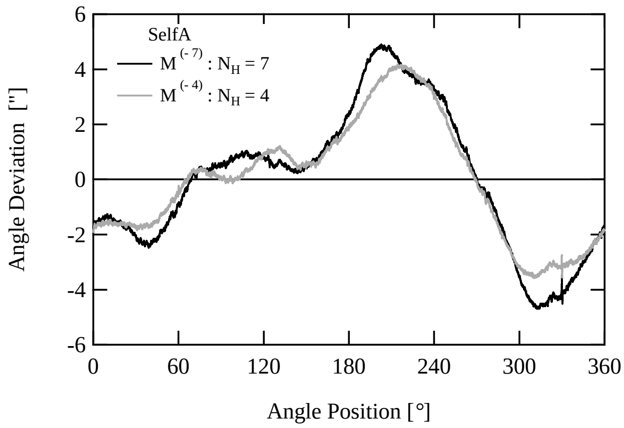

Fig. 3 Self-calibration results $M^{(-7)}$ and $M^{(-4)}$ of N_H =7 and N_H =4 SelfA in MC-SelfA.

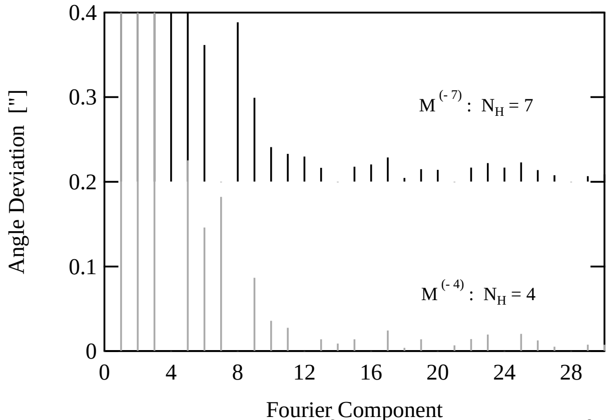

Fig. 4 Fourier component (frequency component) of Self-calibration results $M^{(-7)}$ and $M^{(-4)}$ of N_H =7 and N_H =4 SelfA.

For example, as shown in Figure 2, if the number of sensor heads is N_H =10, the calibration curve do not include 10th order frequency components. So, in order to get high-precision calibration curve containing up to higher frequencies, many sensor must be arranged. Therefore, we propose Multi Combination SelfA (MC-SelfA) which is use two sets of sensor heads combination of N_H =7 and N_H =4 as shown in Figure 2. Figure 3 shows calibration curves for N_H =7 and 4, each frequency component is shown in Figure 4 respectively. With regard to each frequency component, 7th order components are not found when N_H =7 as well as, 4th order components are not found when N_H =4. However, the lack of frequency components can be compensated using frequency components of the other calibration curve other than 28th order frequency components which is the least common multiple (L.C.M) of 4 and 7. The results are shown in Figure 5 and the frequency components are shown in Figure 6.

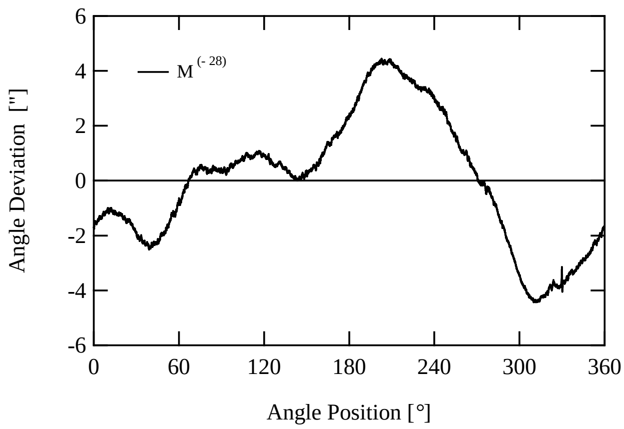

Fig. 5 Combined calibration results $M^{(-28)}$ by using N_H =7 and N_H = 4 SelfA in MC-SelfA.

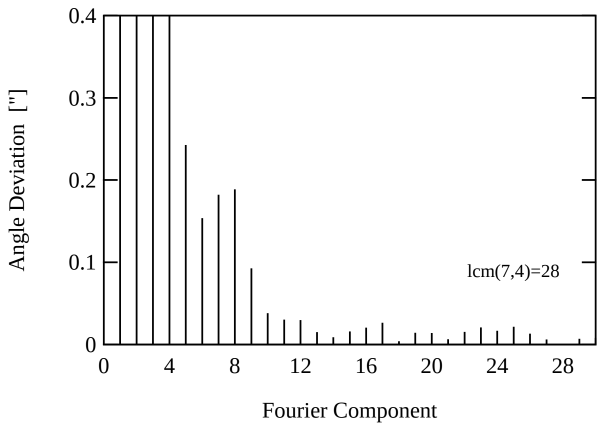

Fig. 6 Fourier component (frequency component) of Combined calibration results by N_H =7 and N_H =4 SelfA in MC-SelfA. Only 28th order frequency components are unknown.

2.2 Phase Shift combination method

In order to compensate the specific frequencies of each calibration curve, generally we use the analysis of Fourier transform and invers Fourier transform. Here we explain the phase shift combination method which is much simpler calculation method using the law of the Fourier series against periodic curves as above mentioned. Each calibration value of N_H =7 and 4 represent $M^{(-7)}$ and $M^{(-4)}$, and create 7 curves by using $M^{(-4)}$, $M^{(-4)}$ shifts 7 times of the angular phase shift of 360 ° / 7 order, and calculate its mean value $M^{(-4)}{}_{(7)}$ as shown in Figure 7.

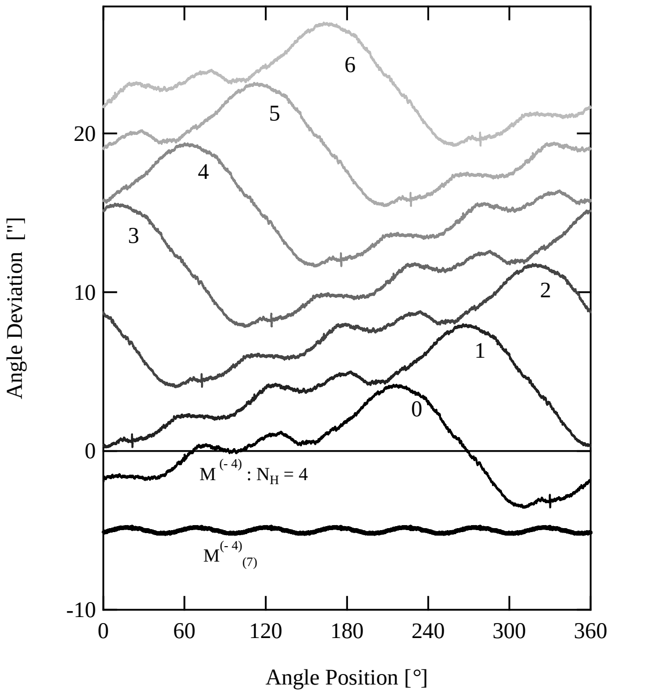

Fig. 7 Phase shift of $M^{(-4)}$, and the mean value $M^{(-4)}_{(7)}$ of 7 curves of Phase shift of $M^{(-4)}$

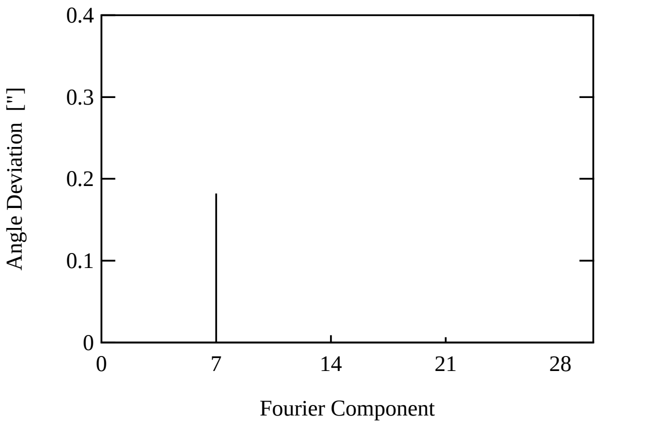

Fig. 8 Fourier component (frequency component) of the mean value $M^{(-4)}_{(7)}$.

According to the law of Fourier series, this mean value $M^{(-4)}_{(7)}$ has only 7th order components other than 28th order components because $M^{(-4)}$ does not include 4th order components from the first. Figure 8 shows the Fourier component of the mean value $M^{(-4)}_{(7)}$. Combined calibration results $M^{(-28)}$ in figure 5 is evaluated from simple add of $M^{(-7)}$ figure 3 and the mean value $M^{(-4)}_{(7)}$ in figure 7 with the following formula,

$$M^{(-28)} = M^{(-7)} + M^{(-4)}_{(7)}. \tag{3}$$

3. Experiment and Results

3.1 Rotary table built-in MC-SelfA encoder

We developed the rotary table built-in MC-SelfA, figure 9 shows the picture of the SelfA47-table. This table uses an air bearing (AB-80: CANON), 10 pieces of sensor heads (SMD-01: SEIKO NPC CORPORATION) are arranged as shown in fig. 2(right side). This SMD-01 is a high-precision optical encoder that employs a diffraction image projection method. It incorporates an OEIC (Opto-Electric Integrated Circuit) and LED light source in a single package. Miniature clear-mold package size is (5.3×4.3×1.68mm), and its resolution is 20 μm pitch pattern scale. The rotary scale disc (KOSHIBU PRECISION CO., LTD.) has 18000 graduation lines and its scale pitch is 20 μm and angle interval corresponds 72". The work table of the SelfA47-table is controlled by servo motor control.

Fig. 9 The SelfA47-table is the rotary table built-in MC-SelfA.

3.2 Calibration of Rotary Encoder

We demonstrate the calibration experiment of rotary encoder (RON905: HEIDENHAIN) and compare the calibration data taken by the primary angular standard of Japan in AIST (uncertainty is 0.01")[3] [4] [5] [6]. Figure 10 (left side) shows the SelfA47-table measuring RON905. Figure 11 shows the calibration results by SelfA47-table and the primary standard.

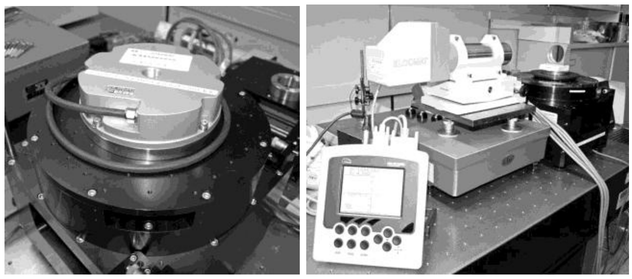

Fig. 10 The SelfA47-table measures a rotary encoder (left side), and an autocollimator (right side).

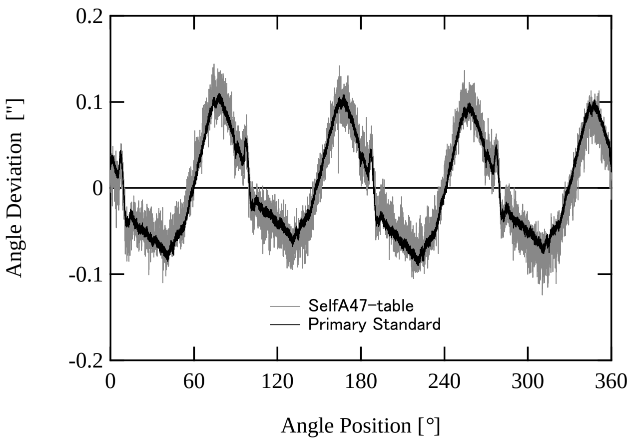

Fig. 11 Calibration results of RON905 rotary encoder by the SelfA47-table and the primary angular standard of Japan.

RON905 encoder has typical 4 periodic angle errors within ±0.2". Both the SelfA47-table and the primary angular standard of Japan detect very close angle error calibration results from RON905. The deviation between two calibration data is smaller than ±0.04". The measurement time is very short, during rotary table rotates one rotation both data acquisition of self-calibration for SelfA and rotary encoder to be calibrated are carried out. When rotation speed is 10 rpm, measurement time is 6 seconds.

3.3 Calibration of Autocollimator

We demonstrate the calibration experiment of autocollimator (Elcomat 3000: Möller-Wedel) and compare the calibration data taken by the primary angular standard (uncertainty is 0.03" for autocollimator). Figure 10 (right side) shows the setup of SelfA47-table and Elcomat 3000. Figure 12 shows the calibration results by SelfA47-table and the primary standard. Primary standard has 25500 graduation lines encoder, so the angular interval becomes 5.76", on the other hand, SelfA47-table has 18000 graduation lines which corresponds 72" angular interval. Thus, two measurement intervals are different as shown in the figure 12. The SelfA47 table can detect angle error of the autocollimator on high accuracy like measurement of rotary encoder.

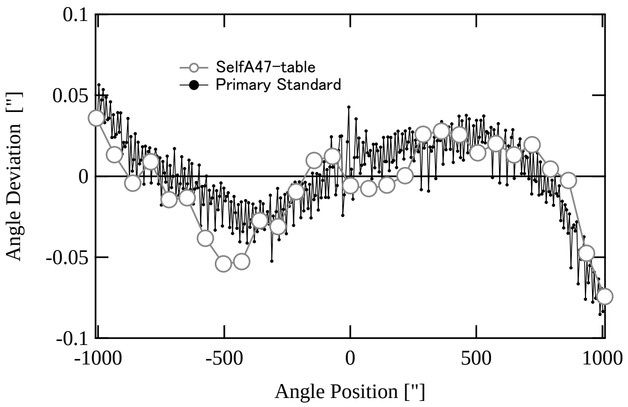

Fig. 12 Calibration results of Elcomat 3000 autocollimator by the SelfA47-table and the primary angular standard of Japan.

4. Conclusions

SelfA is very useful encoder can detect the angular error itself without using external equipment. However it has weak point which the calibration curve does not include frequency components same as the number of multiple sensor heads. For this reason, total accuracy of SelfA encoder has limitation. To overcome its weak point, our research introduced to the MC-SelfA principle. Because MC-SelfA can evaluate the higher frequency components in a small number of sensor heads, the calibration curves can have much higher accuracy.

ACKNOWLEDGEMENT

This research was supported as part of "Grant for Industrial Technology Research" program by The New Energy and Industrial Technology Development Organization (NEDO).

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