Application of a self-calibratable rotary encoder

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Abstract

National Metrology Institute of Japan (NMIJ) developed a self-calibratable rotary encoder (SELFA) [1] that can detect angle deviations of its scale disc and an attachment eccentricity error. In this research, NMIJ made a rotary table installed this SELFA encoder for checking performance of angle deviation detective function. It has detected some kinds of angle deviation factors, not only scale angle deviation and eccentricity error, but also ball bearing error and the equipment body distortion effect caused by weight load on the work table. The SELFA mechanism is very simple. However, the accuracy reached to about 0.3” or more. This rotary table with built-in SELFA is expected as a simple angular standard instrument for small and medium-sized enterprises.

Keywords: Rotary encoder, self-calibration, uncertainty, angle, standard

1. Introduction

A rotary encoder spreads as an important sensor used for angular measurement or control in a broad industrial field, and its quantity is also increasing firmly by production expansion of semiconductor industry and the auto industry, etc. in recent years. However, rotary encoder does not output the ideal angular information, in short, outputs angle positional information with the various kinds of angle deviations, so users need to recognize what kinds of angle deviation factors exist, and expect to be able to do ideal angle control by correcting those angle deviations.

The angle deviation of a rotary encoder installed in instruments is roughly classified into two kinds of factors,

1) Static angle deviation factor
   1-1) Angle scale error
   1-2) Attachment eccentricity error

2) Dynamic angle deviation factor
   2-1) Equipment mechanics error
   2-2) Equipment distortion and aging error.

Static angle deviation factor is due to a typical angle positional deviation of real scale graduation lines position from ideal equivalent interval graduation line position, and eccentricity between scale disc and encoder shaft, or between an encoder shaft and equipment shaft. Dynamic angle error factor is due to mechanical distortion of equipment or device parts quality like bearing motions.

In this research, in order to study the performance of self-calibration rotary encoder, we developed a rotary table with build-in SELFA (Fig. 3) and we verified detection capability of the quantitative of angle deviations.

2. Principle of self-calibratable rotary encoder (SELFA)

SELFA encoder mechanism is very simple that several number of sensor heads are arranged around one scale disc at same angle interval as shown in Fig. 1. One arbitrary sensor
head A₁ is chosen as a main head. While scale disc is rotating one revolution, comparison measurement of the angular signal difference $\delta_{i,(1,j)}$ from between the main head and other heads output is carried out, where, $i$ ($i = 1, 2, \cdots, N_G$) represent a graduation line number, $N_G$ is the total graduation line number of a rotary encoder, $j$ ($j = 1, 2, \cdots, N_H$) 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 signal of the $i$-th position, then the $j$-th reading head detects signal from the $(j-1) N_G / N_H$ graduation line position at same time as shown in Fig.2. Therefore, the signal difference $\delta_{i,(1,j)}$ is written as follows:

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

(1)

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

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

(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 2π periodic curve can be expressed by the Fourier series, and when $n$-number of curves with a phase shift of $2\pi/n$ at a time are averaged, the averaged curve shows the sum of an integral multiple of $n$-th times order of Fourier components of the original curve”.

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

### 3. Rotary table with SELFA

Figure 3 shows the rotary table with self-calibratable rotary encoder. Although a base plate is a product made from stainless steel, a bearing box portion is made from aluminum. The ball bearing is used to the axis of rotation, and its axial rotation accuracy is about 0.5 μm.

![Fig. 3. Rotary table with SELFA (N_H = 10 sensor heads).](image)
SELFA encoder is set up in the bottom of this device, and ten sensor heads are used. The sensor head is Mercury 3000 made by MicroE systems company. The scale has 23049 graduation lines in 360° with interval of 20 μm, so that one angle pitch interval becomes 56.2°.

4. Experiment-1: calibration data and repeatability

In an experiment-1, we studied the performance of an angle deviation detection function. We rotate the work table 10 revolutions and obtained 10 calibration data as shown in Fig. 4. All calibration data lines have 25° peak-peak deviation, and distribute about ±0.3° from averaged data as show in Fig. 4 and Fig. 5.

![Fig. 4. Self-calibration results by SALFA and estimation of an eccentricity by sin fitting calculation.](image1)

![Fig. 5. Repeatability of calibration data.](image2)
According to the amplitude of fitting data of one sinusoidal sine wave which appears in a calibration curve under the influence of eccentricity, the scale disc center of this SELFA can be adjusted at its eccentricity of about ±8″ that is corresponded to 2.8 μm (=8″*20 μm/56.2″). Therefore, residual error that is the difference between the calibration value and the fitting value shows the angle deviation of the scale graduation line from nominal angle position. The source of this non-repeatability of ±0.3″ is cased by non-uniformity of revolution of balls which are rotating in the bearing. Since rotation of a ball and rotation of a table are asynchronous, it shows the deterioration of repeatability as shown in Fig. 5.

If we would not get the calibration date for this rotary table, we have to use it with its accuracy of about 30″. Now we can get the calibration data at any time only one revolution rotation, and start positioning and control the angle motion within 100 times better accuracy of ±0.3″.

5. Experiment-2: equipment distortion factor by weigh load

In an experiment-2, we studied how to detect an equipment distortion angle error for the dynamic angle error, for example, the weight load on the work table. We set up a weight on the table and measured its calibration data. Figure 6 shows the experiment results of the two calibration curves, one is normal setup without weight and another is 5 kg weight load.

The difference of two data is caused by body distortion of rotary table. This body distortion makes a distortion of the rotary encoder scale or a miss arraignment of sensor heads position diffusively. These two calibration data have same repeatability of ±0.3″ respectively. So, user can obtain fresh calibration data at any time in only one revolution rotation.

![Graph showing calibration data](image)

Fig. 6. Difference of calibration data between normal and weight load.

6. Conclusion

Experiment-1 calibration data shows scale deviation and eccentricity error for the static angle error factor, and bearing error that is classified into an equipment mechanics error for one of the dynamic angle error. Experiment-2 shows an equipment distortion error of the dynamic angle error. In this research, we fined this SELFA self-calibration function can detect not only static angle error factor caused by encoder itself, but dynamic error caused by
outside error sources, for example weight load, inclination of body of rotary table, torque force against the table shaft rotation.

User demanded the high resolution and good repeatability of rotary encoder in angle control, however, in recent year, high precision angle detection 1” and more capability as an absolute value is demanded further more. This SELFA might be expected as next generation tool for high precise angle detection function and real-time angle calibration.

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References