

# EVALUATION OF DYNAMIC SPINDLE RUN OUT ABILITY OF SELF-CALIBRATABLE ROTARY ENCODER

Tsukasa Watanabe, Yohan Kondo, Hiroyuki Fujimoto

National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8563, Japan.  
t.watanabe@aist.go.jp, kondou.y@aist.go.jp, h.fujimoto@aist.go.jp

**Abstract:** SelfA (Self-calibratable Angle device) encoder is an epoch-making encoder with the angular error self-calibration function. SelfA encoder, which has the structure of arranged several sensor heads around the scale disc at the equal angular interval space, by analyzing the angle signal from each sensor heads output in one revolution, can detect several angular error factors, not only angle scale error but an attachment error (eccentricity error). Because SelfA can carry out this self-calibration analysis after attached to the axis shaft of the apparatus, even if measurement condition changes, the people can use the encoder keeping the same angle accuracy. The SelfA encoder can achieve angle accuracy more than 0.1" by this function.

In this SelfA study, we find out that there was slight difference between the output angle signals in each SelfA sensor heads, furthermore, understand the slight difference is generated from axis shaft run out of the apparatus.

In order to estimate the ability of run out detection function of SelfA encoder quantitatively, we developed an axis run out generating device and carried out the experiment. In this experiment results, SelfA can detect dynamic RRO (Repeatable Run Out) and (NRRO: Non Repeatable Run Out) with very high sensitivity of accuracy about 50 nm level

**Keywords:** Spindle, Run out, Angle, Self-calibration, Rotary Encoder

## 1. INTRODUCTION

In general, methods for measuring shaft run out of a rotation axis are mainly using a contact method with an electric micrometer or a non-contact method with a capacitance sensor. The contact method cannot be utilized with a high-speed rotation axis, and when the capacitance sensor in the non-contact method is used, it takes a lot of time to set up the measurement alignment because the gap between a rotation axis to be measured and the sensor is very narrow. Further, since the cost of laser-type is very expensive, so it is a problem the cost is too high when we use two sensors for X and Y axis [1], [2].

AIST has studied technical development which detects the angular error of a rotary encoder and has developed SelfA (Self-calibratable Angle device) encoder [3-7] which can detected some kinds of angular error, not only its encoder scale error and the attachment error (eccentricity error), but also ball bearing error (NRRO: Non Repeatable Run Out) and its body distortion effect caused by weight load from outside [6]. Since NRRO can be estimated from the deviation of a calibration value in the repeatability measurement, NRRO separation method from the calibration value of a rotary encoder have been reported [8].

However, since RRO (Repeatable Run Out) synchronizes with shaft rotation angle, it is difficult to separate and to detect only RRO from the angular error of a rotary encoder. Therefore, the detection method of RRO by attaching an external sensor to the rotation shaft is very common.

SelfA encoder is installed several of sensor heads and analysis the signal processing from those sensors. We find out the RRO separation analysis method from slightly systematic angular error deviation between each sensor heads. When this SelfA encoder is rotated only one revolution, it can be calibrated with a high angular accuracy, and can detect dynamic spindle run out with a high sensitivity. This paper describes a qualitative concept about shaft RRO run out separation method from SelfA encoder analysis.

## 2. PRINCIPLE

### 2.1 SelfA Encoder Principles

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  $A_1$ . The angle deviation  $a_{i,j}$  from an ideal graduation line position that  $j$ -th head detects, when  $A_1$  detects  $i$ -th graduation line signal, represents,

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

When  $A_1$  detects  $i$ -th graduation line signal, the  $j$ -th head detects the  $i + (j - 1) N_G / N_H$  graduation line at same time. Where,  $i$  ( $i = 1, 2, \dots, N_G$ ) represents a graduation line number that the main head  $A_1$  detects,  $N_G$  is the total graduation number of a rotary encoder,  $j$  ( $j = 1, 2, \dots, N_H$ ) is a sensor head number and  $N_H$  is the total number of sensor heads. While the scale disc rotating one revolution, data acquisition of the angular signal difference  $\delta_{i,(j,k)}$  between the head  $A_j$  and other head  $A_k$  output are carried out. The signal angular difference  $\delta_{i,(j,k)}$  is written as follows,

$$\delta_{i,(j,k)} = a_{i+(j-1)N_G/N_H} - a_{i+(k-1)N_G/N_H} . \quad (2)$$

The difference  $\delta_{i,(j,k)}$  is calculated to each sensor head  $k$ , and the mean value  $E_{i,j}$  is expressed by the following formula,

$$E_{i,j} = \frac{1}{N_H} \sum_{k=1}^{N_H} \delta_{i,(j,k)} \\ = a_{i+(j-1)N_G/N_H} - \frac{1}{N_H} \sum_{k=1}^{N_H} a_{i+(k-1)N_G/N_H} . \quad (3)$$

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  $2\pi$  can be expressed by the Fourier series, and when n-number of curves with a phase shift of  $2\pi/n$  at a time is 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  $E_{i,j}$  represents the calibration data of rotary encoder, however it does not include  $nN_H$ -th order Fourier components corresponding to 2nd term of right side in equation (3). Figure 2 shows the calibration results of  $E_{i,j}$  ( $j=1, 2, \dots, 8, N_H=8$ ) at the different sensor heads at position  $j$  respectively. The circle stamps with number  $j$  show the position where  $j$ -th sensor head detects a scale line number 1 or index signal from rotary encoder (Angle position Stamps: AS), and triangle stamps with number  $j$  represent position of a scale number of the scale disc that is detected when the  $j$ -th sensor head starts measurement ( $i=1$ ) (Time Stamps: TS). In general, eight data in Figure 2 should show the same calibration value if those angle phases are shifted according to the difference in the position of each sensor head  $2\pi j/N_H$  ( $=45^\circ$  at  $N_H=8$ ) by the difference in the position of each reading head, five data should show the same calibration value.

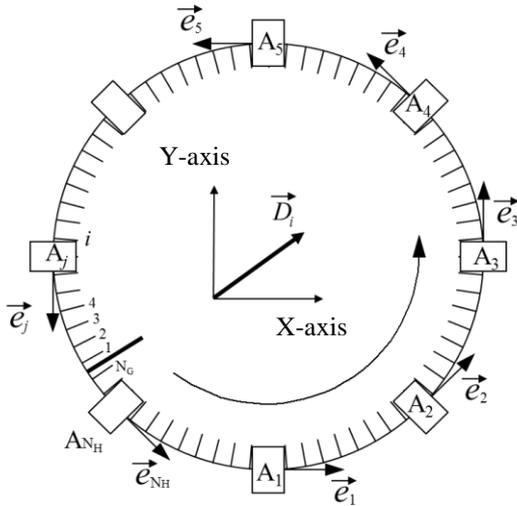


Figure 1 Layout sketch of the SelfA Rotary encoder with the sensor head  $A_j$ . The unit vector  $\vec{e}_j$  indicates the direction of the scale lines train at the sensor head  $A_j$ .

## 2.2 Ron out Detection Principle from SelfA encoder

In the section 2.1, equation (3) includes only the static angular error factor caused by scale error and shaft eccentricity. However, dynamic error factor caused by shaft run out is not taken into consideration. Since a static angular error change depending on a scale number, each sensor heads detect the same error value at any scale line position. The RRO dynamic angular error shows same value at  $j$ -th sensor head position. Therefore, total error  $a_{i,j}^D$  including both static and dynamic error is represented as follow,

Figure 2 of a calibration data by  $N_H=8$  SelfA encoder. In one revolution rotation, SelfA can output the eight calibration analysis results corresponded to the sensor head. From this results, an attachment eccentricity error is estimated about 30”.

$$a_{i,j}^D = a_{i,j} + (\bar{D}_i \cdot \vec{e}_j) \quad , \quad (4)$$

where, 1st and 2nd terms of right side in equation (4) represent static and dynamic angular error respectively.  $\bar{D}$  is dynamic angular error vector at the timing of the main head  $A_1$  detects  $i$ -th scale line, and  $\vec{e}$  is a unit vector in a tangential direction at the scale disc of  $j$ -th sensor head position as shown in Figure 1. This inner product represents the projection length of dynamic angular error to the unit vector at each sensor head (PLD). By using the equation (4), the equations (2) and (3) are represented as follow with dynamic angular error vector,

$$\begin{aligned} \delta_{i,(j,k)}^D &= a_{i,j}^D - a_{i,k}^D \\ &= a_{i,j} - a_{i,k} + [(\bar{D}_i \cdot \vec{e}_j) - (\bar{D}_i \cdot \vec{e}_k)] \quad , \quad (5) \end{aligned}$$

$$\begin{aligned} E_{i,j}^D &= \frac{1}{N_H} \sum_{k=1}^{N_H} \delta_{i,(j,k)}^D \\ &= E_{i,j} + \left[ (\bar{D}_i \cdot \vec{e}_j) - \frac{1}{N_H} \sum_{k=1}^{N_H} (\bar{D}_i \cdot \vec{e}_k) \right] \\ &= E_{i,j} + (\bar{D}_i \cdot \vec{e}_j) \quad , \quad (6) \end{aligned}$$

$$\therefore \sum_{k=1}^{N_H} (\bar{D}_i \cdot \vec{e}_k) = 0 \quad . \quad (7)$$

The 1st term of right side in equation (6) shows the static angular error that is detected same value at all of sensor heads as shown in equation (2). The 2nd term of right side in equation (6) shows difference in the position of each sensor head. Therefore, if the static angular error component included in common, PLD can be evaluated from the analysis of mean value of  $E_{i,j}^D$  is subtracted from the calibration value  $E_{i,j}^D$  of each sensor head shown in Figure 2.

## 3. EXPERIMENT

### 3.1 Run out Generator System

In order to evaluate the run out ability of SelfA encoder, we developed the run out generator system shown in figure 4. The run out generator, SelfA encoder and spherical ball are attached on the same axle shaft of an air-bearing. The run out generator has mainly two parts, one is disc plate that is attached the shaft with small eccentricity about 1 mm, and another part is several balls that are arranged around the disc plate. When the disc plate is rotating with shaft and it contacts the push-ball, the disc plate is pushed toward the center direction, and as the result of the shaft displacement, the quantitative shaft run out is obtained by fine adjustment

of the push-ball position by a micrometer. The evaluation of the quantitative run out value is measured by using a laser length measuring device that detects the length change in position of the spherical ball placed at the upper end of the shaft. As for the laser length measuring device, we used the Laser Run out Sensor & Meter RR-2000 system. RR-2000 system has the laser Doppler system that can be detected with high resolution up to 0.07 nm (70 pm) from the detection distance of 100 mm occurs in a rotationally-body rotation axis a small run out the (NRRO / RRO).

### 3.2 Run out Experiments

Experiment was carried out by using  $N_H=8$  sensor heads SelfA encoder, its scale has 18,000 graduation lines and the line pitch is 20  $\mu\text{m}$ . The sensor head is SMD-01 optical encoder head made by SEIKO NPC CORPORATION. The 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. Two push balls are installed at the position along the X axis and Y axis, and the shaft is rotating CW direction from the top view as shown in figure 3.

Figure 4 shows the calibration results of  $N_H=8$  sensor heads SelfA encoder attached into the run out generator system. As a feature of the measurement results in fig.4, the influence of the eccentricity due to the attachment is smaller as compared to the results of Figure 2. At first, the disc plate which rotates synchronously with the shaft generates run out where rotated through approximately 30 degrees in contact with the push-ball was placed on the X-axis, at a location rotated 300 degrees further, it generates run out of second time in contact with the push ball was placed on the Y-axis.

The data in Figure 4 shows that AS is different and TS is the same as shown in Figure 2. Therefore, it is possible to estimate the angular error corresponds to first term of equation 6 from the mean value of the eight data after

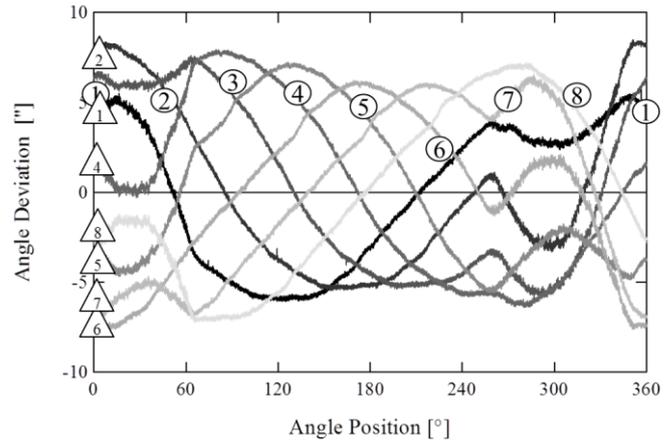


Figure 4 Calibration data of  $E^D_{ij}$  by SelfA encoder ( $N_H=8$ )

matching the angular phase of the AS. the values were analyzed by subtracting the angle error obtained as an average value from the eight data shown in Figure 4 is shown in Figure 5. This each value correspond the 2nd term of right side in equation (6). That is, FIG 5 shows the run out magnitude values obtained by projecting the unit vector  $\vec{e}$  direction of each sensor head respectively of the shaft run out which occurs when  $A_1$  has detected  $i$ -th scale line.

It is possible to determine the run out of the shaft using eight data shown in figure 5 by projecting the XY-axis plane such as shown in Figure 1. In this experiment, we use the scale disc that has the total graduation number of a rotary encoder  $N_G = 18000$ , the one scale pitch is corresponded to  $72''$ , and the pitch distance between scale lines is 20  $\mu\text{m}$ . That is,  $2''$  of the dynamic angle error of figure 6 is corresponded to about 0.56  $\mu\text{m}$  when it converts into length,

$$20 \mu\text{m} \times \frac{2''}{72''} \cong 0.56 \mu\text{m} \quad (8)$$

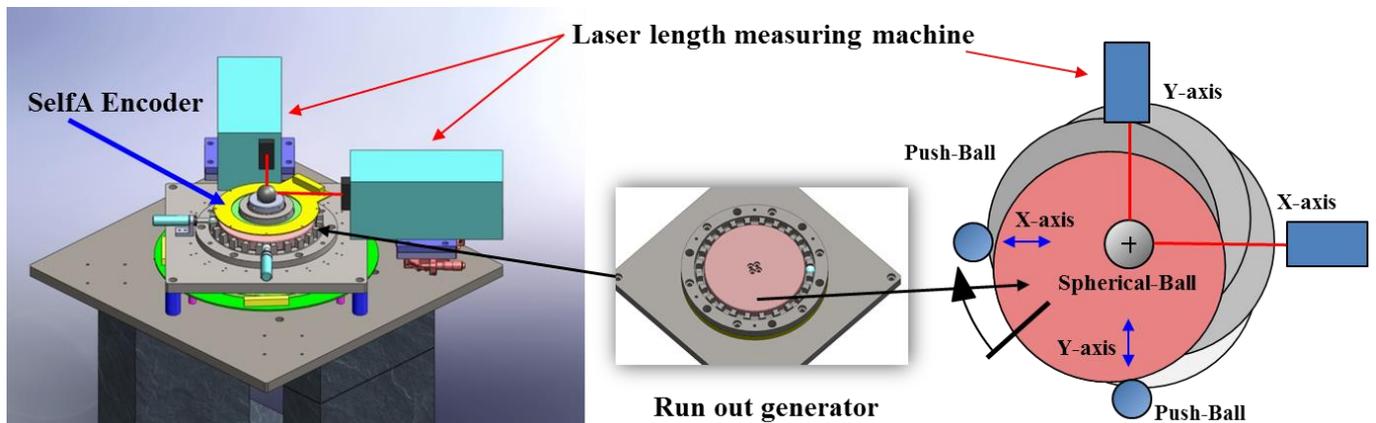


Figure 3 Run out generator by Laser length measuring machine. The SelfA encoder is installed into the system that is mounted coaxially to the shaft axis from an air bearing.

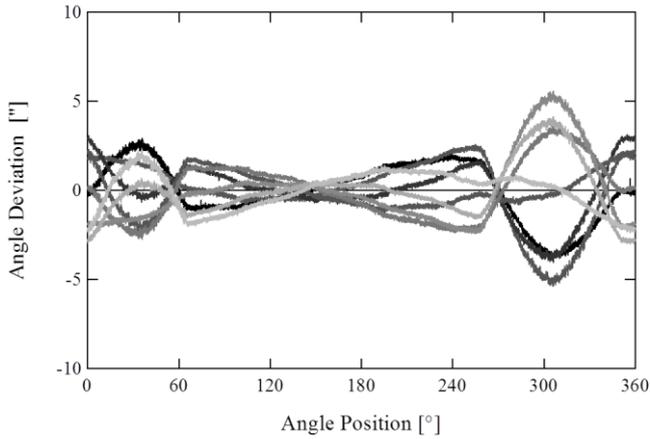


Figure 5 This each value correspond the 2nd term of right side in equation (6).

#### 4. CONCLUSIONS

The rotary encoder using the principle of the SelfA with a self-calibration function has so far developed as apparatus which outputs highly precise angular error information. However, in this paper, it turned out that SelfA rotary encoder can detect not only static angle error, but also dynamic angle error as shaft run out (RRO).

This paper discussed separation method of the static angle error represented with a scale error or an eccentricity error and the dynamic angle error represented with shaft run

out from the angle error from SelfA encoder data in a quantitative way. In order to quantitatively evaluate the run out detection capability SelfA, we developed a run out generator system, and performed comparative experiments with the laser length measuring machine. As a result, as shown in figure 6, we found out SelfA can detect the shaft run out with an accuracy of 100nm or less.

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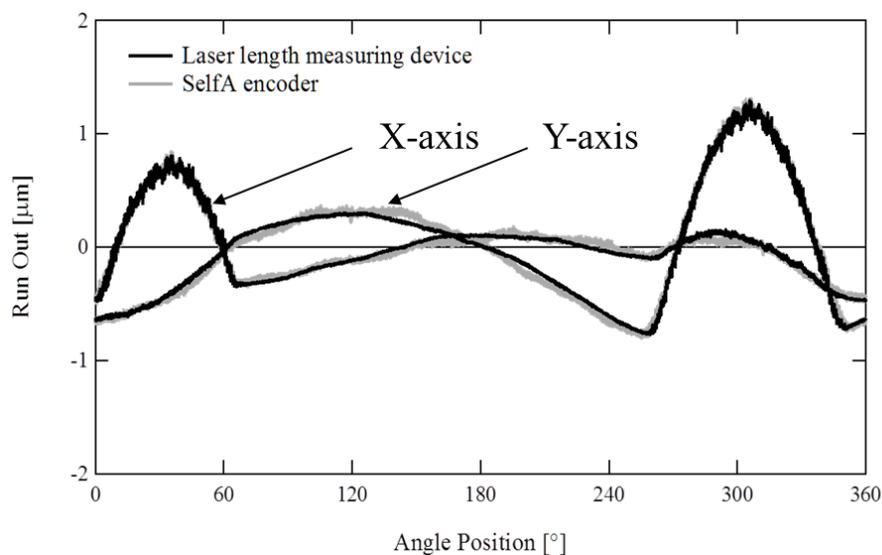


Figure 6 Run out value analysed by SelfA encoder and the laser length measuring device. The deviation of two methods is smaller than 0.1 nm.