Self-Calibratable Rotary Encoder

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Abstract. In National Metrology Institute of Japan (NMIJ)/AIST, the rotary encoder calibration system is developed as the national primary standard for an angle, and highly precise standard calibration service is supplied from 2003. The source of uncertainty that influences most greatly in calibration is the attachment error (eccentricity) of a rotary encoder. Even if users get the calibrated rotary encoder, the error when attaching in using apparatus cannot be estimated. In NMIJ, we developed the new rotary encoder that can be calibrated by rotary encoder itself. Its mechanism is very simple; some reading heads are arranged at the equal angle interval around a scale disk. The calibration curve that contains not only all graduation lines deviation but eccentricity can be obtained by analyzing in series the signals acquired from heads. In order to check the performance of this epoch-making rotary encoder, we set up this system on the national primary standard and compared this self-calibration data with the data by using the primary standard system. The accuracy for 0.5 ″ or less could be acquired. Since this method is applicable also to a small rotary encoder, it is expected that the self-calibratable rotary encoder be used in many angle control instruments.

1. Introduction
In NMIJ, the rotary encoder self-calibration system using the equal division averaged method (EDA-Method)[1, 2] which is one of the self-calibration methods is developed, and highly precise angle standard supply to which expanded uncertainty becomes 0.01 ″ has been realized. However, this system only calibrates the graduation line signal, and the accuracy after attaching a rotary encoder in use apparatus is not guaranteed. Thus, for the reasons of the influence caused by the rotary encoder’s attachment error, a secular change and the deformation by the environment, the encoder outputs the graduation signals with unknown error value caused by these error factors. Therefore, in order to judge the output signal from an encoder correctly, it is very important that we calibrate it after building an encoder into using apparatus. Figure 1 shows the deviation as a rotary encoder calibration curve between the certain graduation line position and an ideal graduation position, the fitting result of this calibration curve on the assumption of an eccentricity error and its residual value. The one big amplitude periodic curve explains the existence of an attachment eccentricity etc.. The latest highly precise rotary encoder also has the eccentricity canceling mechanism by attaching two reading head s in the 180 ° countered position on the scale disk. However, there is no rotary encoder that can detect quantitatively the amount of canceled eccentricity after attaching. In this research, we designed and developed a rotary encoder that the self-calibration function is built in the rotary encoder itself using the EDA-method, such as having been adopted as the angular national standard system of Japan.
2. Development Concept

Since an angle has the peculiarity that is the $360^\circ$ closed system, even if it does not compare with a highly precise angle machine, rotary encoder itself may be able to be calibrated using a self-calibration method. The EDA-Method is one of the self-calibration methods that can be calibrated simultaneously by comparing the graduation lines of two encoders that a graduation position deviation are unknown. The EDA-Method is the same principle as the multi-orientation techniques (the multi-step method) currently used in case of the roundness measurement[3, 4, 5]. As shown in Figure 2, when we calibrate a rotary encoder B using this EDA-method, the scale disks of two rotary encoders A and B are attached in the same axle, and was rotated, and it has calibrated by the method of detecting and comparing the angle signal from each reading head. However, it is necessary to build in two sets of rotary encoders, so that this mechanism may be enlarged and calibration work becomes complicated because of changing the relative position of two sets of rotary encoders. In order to solve these problems, we made the rotary encoder that

![Figure 1](image1)

**Figure 1.** A rotary encoder output signal with an attachment error.

![Figure 2](image2)

**Figure 2.** Set up of two rotary encoders self-calibration system.

![Figure 3](image3)

**Figure 3.** Set up of self-calibratable rotary encoder.
can calibrate its own graduation lines by arranging some heads arranged at equal angle interval around the scale disk of one rotary encoder as shown in Figure 3.

3. Calibration Principle

Figure 4 shows the position relation between a rotary encoder scale and reading heads arranged at equal angle interval. Where, \( i (i = 1,2,\ldots,N_G) \) represent a graduation line number, \( N_G \) is the total graduation number of a rotary encoder, \( j (j = 1,2,\ldots,N_H) \) is a reading head number and \( N_H \) is the total reading heads number. Figure 5 shows the relation of the deviation of an ideal graduation position and a real graduation position. The amount of deviation of the \( i \)-th graduation position from an ideal graduation position represents \( a_i \). When the first reading head detects the \( i \)-th graduation position, the \( j \)-th head detects the graduation position where shifts graduation phase to the \((j - 1)N_G/N_H\).

Figure 6 shows the example of the order of the angle signal outputted from each reading head. When the first reading head detects the \( i \)-th scale, other reading heads also detect other graduation line signal respectively at almost same time. Then the deviation of the graduation line that the \( j \)-th reading head detected is expressed as \( A_{i,j} \), this \( A_{i,j} \) is obtained by the following equation,

\[
A_{i,j} = a_{i+(j-1)N_G/N_H}.
\]

The difference of the angle signal between the 1st and the \( j \)-th head and the average value are represented by \( \delta_{i,j} \) and \( \mu_{i,j} \) respectively, then those are expressed as follows,

\[
\delta_{i,j} = A_{i,1} - A_{i,j} = a_i - a_{i+(j-1)N_G/N_H},
\]

\[
\mu_i = \frac{1}{N_H} \sum_{j=1}^{N_H} \delta_{i,j} = a_i - \frac{1}{N_H} (a_i + a_i + N_G/N_H + a_i + 2N_G/N_H + \cdots + a_i + (j-1)N_G/N_H). \tag{3}
\]

Here we use the law of the Fourier series written in the following that can be mathematically proved about arbitrary periodic curves, "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 are averaged, the averaged curve shows the sum of an integral multiple of \( n \)-order Fourier components of the original curve". The measurement value \( \mu_i \) of the left side of an Eq. 3 shows that the \( a_i \) value is subtracted by the average value of \( N_H \) number of curves shifted each \( 2\pi/N_H \) angle phase from the \( a_i \) value. From the analysis of the data obtained from the rotary encoder that has arranged the \( N_H \) number of heads, the calibration curve shows the multiple of \( N_H \)-order Fourier components become zero. Although it is necessary to enlarge the number \( N_H \) of heads naturally in order to obtain the perfect calibration curve which does not omit until the high order Fourier components, however generally the high order components have almost small affect. Only by

![Figure 4](https://via.placeholder.com/150)

**Figure 4.** The position relation between a rotary encoder scale and reading heads of self-calibratable rotary encoder.

![Figure 5](https://via.placeholder.com/150)

**Figure 5.** Graduation deviation between an ideal line position and real graduation line position.
taking into consideration the influence from the Fourier components of a low order of $N_H$, we can evaluate a highly precise calibration value enough.

4. Experiments and Result

As shown in Figure 7, the experiment was carried out by arranging the scale disk and five reading heads (ERO725 Heidenhain) on the upper part of the rotary encoder self-calibration system of the NMIJ. In order to measure an angle signal difference $\delta_{i,j}$, the time, which is detected the graduation line signal from each head, is latched at the external counter of a 100 MHz crystal oscillator, and the count is recorded into a memory. When the external counter value corresponding to angle $A_{i,j}$ is set to $T_{i,j}$, the following equation is used for transfer an external counter value into an angle value,

$$\delta_{i,j} = \frac{T_{i,1} - T_{i,j}}{T_{i,j} - T_{i+1,j}} \times \frac{2\pi}{N_G}.$$  \hfill (4)

Since an Eq. 4 transfers the external counter value into the angle at every each graduation interval, there is an effect of suppressing the influence of an angle speed fluctuation to the minimum. Figure 8 shows the three lines, first is the calibration curve as for a self calibratable rotary encoder by the principle explained above using five heads, second is the calibration curve of one head among five heads calibrated by the rotary encoder self-calibration system and third one is the difference of these two calibration curves. It turns out that the error about a maximum of 6 ″ caused by attachment eccentricity etc. was detected and calibrated with high precision. Moreover, the difference with the calibration value by self-calibration system is smaller than 0.2 ″. This result means that it could calibrate sufficiently with high precision even after attaching a rotary encoder. Figure 9 shows the Fourier components of the both calibration curves shown in Figure 8. The multiple 5th-order Fourier components show the bigger defference than the other componets, because of using 5 reading heads. These undetectable Fourier components depending on the number of attached heads becomes the main source of uncertainty of a calibration value. Furthermore, the misalignment and individuality of reading heads are considered as other sources
Figure 7. Experiment setup of the self-calibratable rotary encoder on the rodary encoder self-calibration system in NMIJ.

Figure 8. Calibration results by the angle self-calibration system and the self-calibratable rodary encoder.

of uncertainty. In deed, from the defference between two Fourier components except the multiple 5th-order Fourier components, we can understand the existance of the unknown sources.
5. Conclusion
In this research, the self-calibratable rotary encoder, that can output a calibration value itself using the EDA-method, was developed. Since it can calibrate the error after attaching a rotary encoder in an apparatus only by arranging some reading heads at equal dividing angle positions, this self-calibratable rotary encoder mechanism has very high usefulness. Since all data can be taken only by one turn in calibration procedure, user might be able to control the angle of the apparatus with real time calibration.

6. References
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