euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Method of acquired angle error correction caused by eccentricity and inclination of scale for rotary encoders

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Abstract

Rotary encoders are essential components in various machines for measuring the angular position of rotating axes. These devices must not only offer high accuracy but also function reliably across a range of operational environments. However, angle measurement errors can arise due to factors such as eccentricity between the encoder and the machine, deformation and inclination of the scale, and shaft runout of the rotating axis. While several methods have been developed to minimize these errors, many suffer from drawbacks including increased encoder size, high costs, the need for additional measurement devices, and complex installation processes, limiting their practical implementation.
This study presents a method to correct the acquired angle error due to large eccentricity and inclination of the scale. The method calculates the acquired error by measuring the radial displacement of the scale based on the intensity variation of the angle detection signal. This approach allows the correction of the acquired error due to large scale eccentricity of up to 100 µm and scale inclination of up to 0.38°. This method uses only one sensor head and does not require any other additional devices, thus streamlining installation on various machines. Therefore, this is an effective means of achieving both high accuracy and flexibility across a wide range of operational environments.

Rotary encoder, Angle error, Accuracy, Correction

1. Introduction

Rotary encoders are used in a wide range of industrial fields because high accuracy angle measurement is essential for precision machining [1]. Therefore, in order to use rotary encoders in various machines and environments, it is necessary that they are highly accurate and easy to install. However, the acquired angle error is due to the installation of the rotary encoder on the machine or the changes in the environment. The causes of the angle error include eccentricity between the encoder and the machine, deformation and inclination of the scale, and shaft runout of the rotating axis. Therefore, rotary encoders need to be installed precisely to reduce the acquired error. This process takes time for installation and limits the environment in which they can be used. Various methods have also been used to reduce the acquired error and improve the accuracy of rotary encoders. For example, calibration with another rotary encoder [2-4], use of multiple sensor heads [5-7], and use of additional sensors [8]. However, these methods suffer from drawbacks including increased encoder size, high cost, the need for additional measurement devices, and complex installation processes, which limit practical implementation.

This study presents a novel method for correcting acquired angle errors caused by encoder installation without the need for multiple sensor heads or auxiliary devices. By detecting variations in the angle detection signal's intensity, the radial displacement of the scale can be measured directly using a single sensor head within the rotary encoder. Authors demonstrated the effectiveness of this method for scale eccentricity and deformation [9]. This paper presents the correction of acquired errors caused by larger eccentricity and inclination of the scale. This novel method is an effective means of achieving both high accuracy and ease of installation of rotary encoders on machines.

2. Angle error measurement method

A rotary encoder is composed of a scale with graduations and a sensor head that detects the graduations. The acquired error due to a change in the apparent arc length detected by the sensor head caused by the radial displacement of the scale. Therefore, the angle error can be calculated by detecting the radial displacement of the scale.

The scale with the radial displacement due to scale installation is approximated by n sectors as shown in figure 1. At each rotation angle θ_i $(i = 1, 2, \cdots, n)$, the arc length ΔL_i of a sector with a central angle $\Delta\theta_i$ is represented by the equation 1, with an initial scale radius r and a radial displacement Δr_i.

$$\Delta L_i = (r + \Delta r_i) \times \Delta\theta_i \qquad (1)$$

The output angle by the sensor head depends on the arc length of the scale. Thus, the angle error d_i at the rotational position θ_i is represented by equation 2 where ΔL_k $(k = 1, 2, \cdots, i, \cdots, n)$ is the arc length of a sector with the central angle $\Delta\theta_k$.

$$d_i = 2\pi \frac{\sum_{k=1}^{i} \Delta L_k}{\sum_{k=1}^{n} \Delta L_k} - \theta_i \qquad (2)$$

The radial displacement of the scale can be detected by using a scale with graduations recorded on a cylindrical surface. The intensity variation of the angle detection signal depends on the gap δ between the recording surface and the sensor. In a magnetic encoder, the relationship between the magnetic flux density B of the magnetic graduations on the scale and the gap δ is represented by the equation 3 [10, 11].

$$B \propto e^{-\delta} \tag{3}$$

In a magneto-resistive device, the signal intensity is proportional to the magnetic flux density. Therefore, the relationship between the gap δ and the signal intensity V can be represented by equation 4.

$$\delta = a \times \log V + b \tag{4}$$

The values of a and b are sensor specific constants determined by previous measurement. In this way, the radial displacement of the scale Δr_i can be measured by calculating the gap from the signal intensity variation at each rotational position.

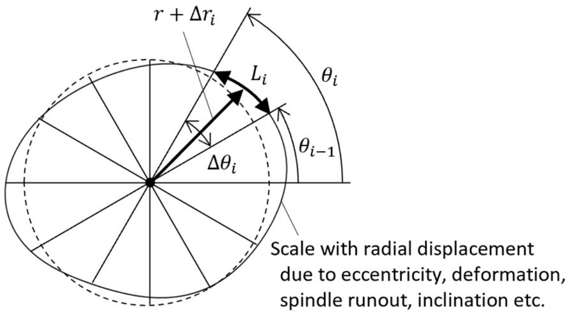

Figure 1. Scale with radial displacement approximated by n sectors.

3. Experimental method

3.1. Experimental setup

The rotary encoder used in this experiment is shown in the figure 2. The scale has magnetic graduations on its outer cylindrical surface, and the sensor head is equipped with magneto-resistive devices arranged to correspond to the graduation pitch of the scale. The scale radius is 95.9 mm, the graduation pitch is 0.4 mm, and the number of graduations per revolution is 1507. The gap between the recording surface of the scale and the sensor head is within 150 µm ± 50 µm. This evaluation rotary encoder is installed onto the accuracy measuring equipment as shown in the figure 3. The accuracy measuring equipment consists of an optical reference encoder and a high precision air spindle with a built-in direct drive motor. The angle error of the evaluation rotary encoder is determined by subtracting the angle output by the reference encoder from the angle output by the evaluation rotary encoder.

3.2. Experimental procedure

The gap and the angle error of the evaluation rotary encoder are measured under each installation condition with different eccentricity and inclination of the scale. The estimated acquired error is calculated based on the change of gap between each installation condition. The actual acquired error is the difference in the angle error measured by the accuracy measuring equipment. The residual angle error is calculated by subtracting the actual angle error measured by the accuracy measuring equipment from the estimated acquired error based on the change of gap.

The gap measurement points are taken at 512 points per rotation as a sufficient number of to approximate the scale with the radial displacement by dividing it into sectors. The present study examined the effects of the scale eccentricity and the inclination of the scale's central axis. The amount of eccentricity of the scale was changed from 20 µm to 100 µm by adjusting the installation condition. The inclination of the scale's central axis was changed up to the inclination φ of 0.38° by adjusting the thickness of the spacer below the scale as shown in the figure 3.

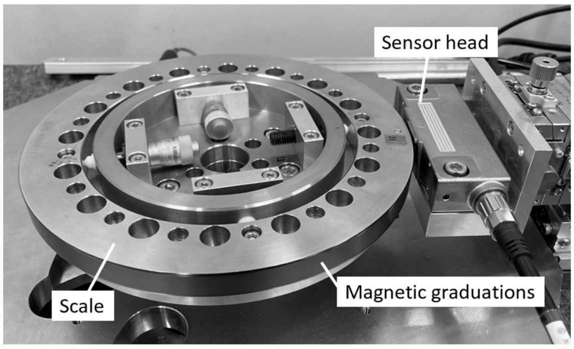

Figure 2. Evaluation rotary encoder.

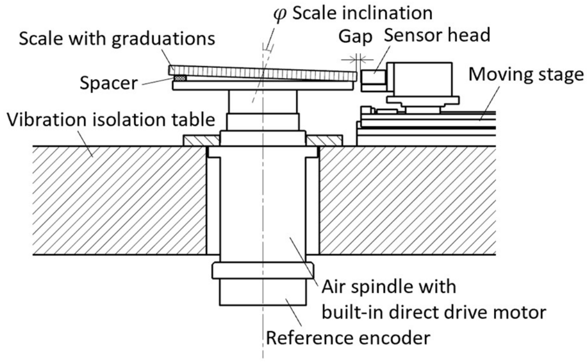

Figure 3. Accuracy measuring equipment.

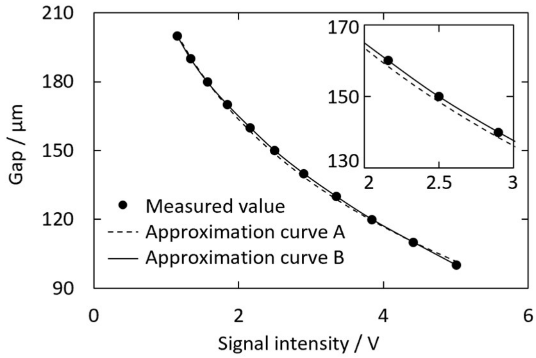

Figure 4. Relationship between the gap and the signal intensity.

3.3 Relationship between the gap and the signal intensity

The signal intensity at each gap is shown in the figure 4. The result of approximating the range of 100 µm to 200 µm using one pair of constants a and b in equation 4 is the approximation curve A. The result of approximating the same range using nine pairs of constants every 10 µm is the approximation curve B.

4. Results and discussion

4.1. Eccentricity of the scale

Under the scale eccentricity of 100 µm, the change of gap and the acquired errors are shown in figure 5, the residual error is shown in figure 6. The gap was calculated by the approximation curve A. In this measurement, the change of gap was 100.11 µm, the acquired error estimated from the change of gap was 216.43″, the acquired error measured by the accuracy measuring equipment was 216.38″, and the residual error was 3.09″. The peak-to-peak values of the acquired errors and the residual error for each change of gap are shown in figure 7. For each change of gap, the acquired error estimated from the change of gap and the acquired error measured by the accuracy measuring equipment were approximately equivalent. However, the residual error increased with increasing the change of gap. Then, Fourier analysis was performed on the residual error, and the amplitude up to the third order component are shown in figure 8. The first order component has a maximum value at the gap change of 20 µm, and a minimum value at the gap change of 100 µm. On the other hand, the second order component increases with increasing the change of gap. This increase in residual error is attributable to errors in the gap calculated from the signal intensity, particularly errors in the gap around 130 µm to 170 µm.

Therefore, in order to reduce errors in the gap calculated from the signal intensity, the gap was recalculated by the approximation curve B, which is approximated with nine equations every 10 µm. The residual error estimated by the approximation curve B under the scale eccentricity of 100 µm is shown in figure. The residual error, which was 3.09″ with the approximation curve A, was 1.30″ with the approximation curve B. The peak-to-peak values of the residual error for each change of gap are shown in the figure. The maximum residual error was 1.61″. By reducing the gap error, the accuracy of the rotary encoder can be improved after correction by this method.

The residual error after correction by this method is compared with the acquired error due to the scale eccentricity. The acquired error due to eccentricity is generally represented by the equation 5 where d/″ is the amount of angle error, e/µm is the scale eccentricity, and r/mm is the radius of the scale [6].

$$d \approx 206\frac{e}{r} \tag{5}$$

For the scale with a radius of 95.9 mm used in this experiment, to ensure the acquired error is 1.61″ or less, the scale eccentricity must be 0.75 µm or less. The installation of the rotary encoder with such precision during the machine assembly process takes considerable time. Therefore, this method of correcting the acquired error is an effective means for achieving both high rotational accuracy on machines and ease of installing rotary encoders.

4.2. Inclination of the scale

Under the scale inclination of 0.38°, the change of gap and the acquired errors are shown in figure 9, the residual error is shown in figure 10. The gap was calculated by the approximation curve A. In this measurement, the change of gap was 11.51 µm, the acquired error estimated from the change of gap was 23.50″, the acquired error measured by the accuracy measuring equipment was 20.61″, and the residual error was 4.64″. The peak-to-peak values of the change of gap, the acquired errors and the residual error for each scale inclination are shown in figure 11. The acquired error due to the scale inclination was reduced by this correcting method. However, the residual error increased with increasing the scale inclination.

The residual error after correction by this method is compared with the acquired error due to the scale eccentricity by equation 5. For the scale with a radius of 95.9 mm used in this experiment, to ensure the acquired error is 4.64″ or less, the eccentricity must be 2.16 µm or less. Installing the rotary encoder with such precision is a time-consuming process. Therefore, this method of correcting the acquired error is an effective means for the inclination of the scale.

However, the residual error in this experiment with scale inclination is larger than the results in section 4.1 with no scale inclination. At the inclination φ of 0.38°, the residual error includes in particular the first order and second order components. The first order component is the acquired error due to eccentricity of the scale. Since the residual error in this experiment with scale inclination is larger than the result in section 4.1 with no scale inclination, the scale inclination caused a difference between the estimated acquired error from the change of gap and the actual acquired error. The second order component is the acquired error due to the inclination of the scale. The shape of the scale detected by the sensor is elliptical due to the scale inclination. In this case, the maximum value of

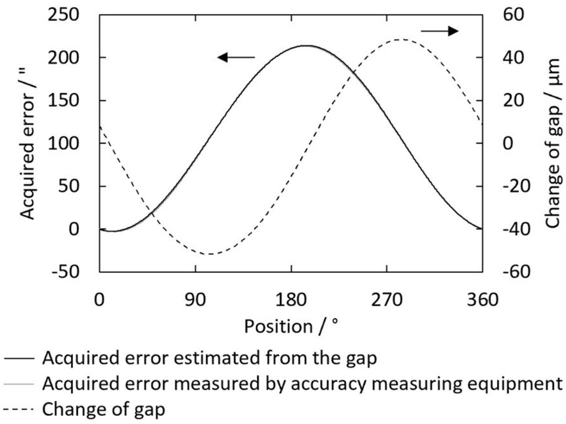

Figure 5. Change of gap and acquired errors at eccentricity of 100 µm.

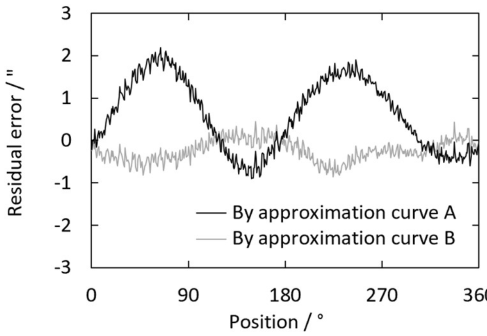

Figure 6. Residual errors calculated by approximation curve A and B at eccentricity of 100 µm.

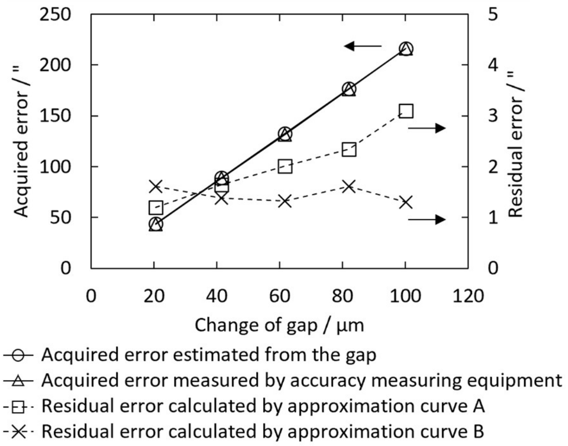

Figure 7. Peak-to-peak values of the acquired errors and the residual error for each change of gap.

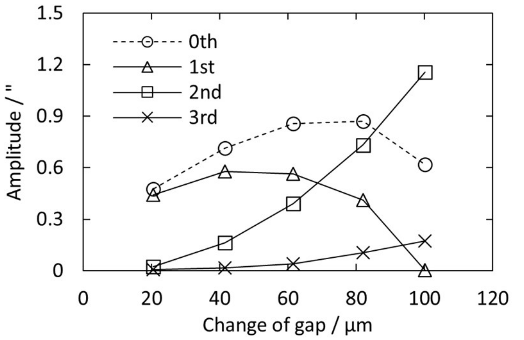

Figure 8. Fourier components of the residual error calculated by approximation curve A.

radial displacement Δr_m at the scale inclination φ is represented by equation 6.

$$\Delta r_m = \frac{r}{\cos\varphi} - r \tag{6}$$

where r is outer radius of the scale. A Fourier analysis was performed on the change of gap at each inclination, and the figure 12 shows a comparison of the amplitude of the second order component with the calculated value using equation 6. There is a difference of approximately 0.2 µm at the maximum inclination. This caused a second order component to appear in the residual error.

The difference in acquired error due to scale inclination is caused by the inclination of the scale's recording graduations relative to the sensor. The graduation pitch becomes longer due to the inclination in the tangential direction of the scale recording surface, which causes an error in the angle detected by the sensor. In addition, the inclination of the scale recording surface in the gap direction changes the magnetic flux detected by the sensor, and the intensity of the angle detection signal also changes. These factors caused the residual error to increase in this experiment with scale inclination. Therefore, to further improve the measurement accuracy, it is necessary to consider these effects of the scale inclination.

5. Conclusion

In this paper, we demonstrated the correction of acquired errors due to larger eccentricity and inclination of the scale using the method based on the intensity variation of the angle detection signal by the sensor head in a rotary encoder. Experimental verification showed that the accuracy of the rotary encoder is improved to less than 1.61" by using this method to correct the acquired error due to the scale eccentricity of 100 µm. It was also shown that the acquired error due to scale inclination is reduced to 4.64" or less. This method is an effective means of achieving both high accuracy on a machine and ease of installing the rotary encoder to a machine. Once the angle error due to the scale installation is corrected, there is no need to correct it again unless the installation condition of the scale is changed. In order to further improve measurement accuracy, it is necessary to consider the change of the signal detection by sensor head due to the scale inclination.

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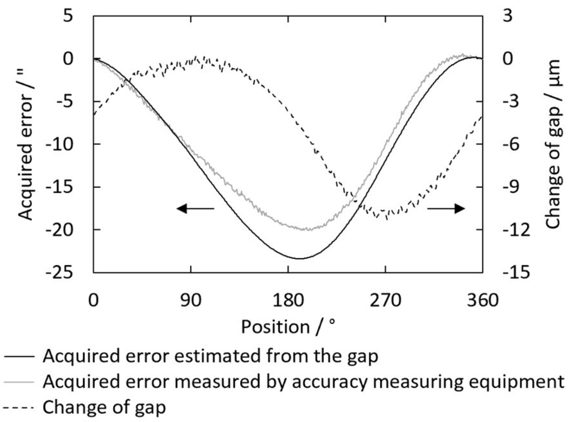

Figure 9. Change of gap and acquired errors at inclination of 0.38°.

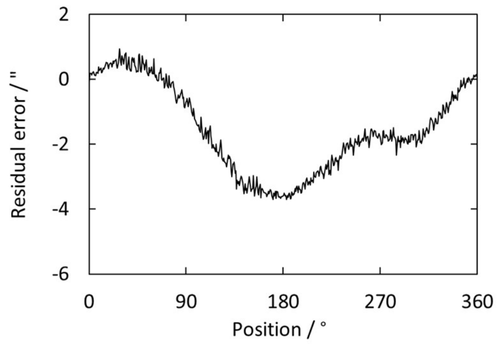

Figure 10. Residual error at inclination of 0.38°.

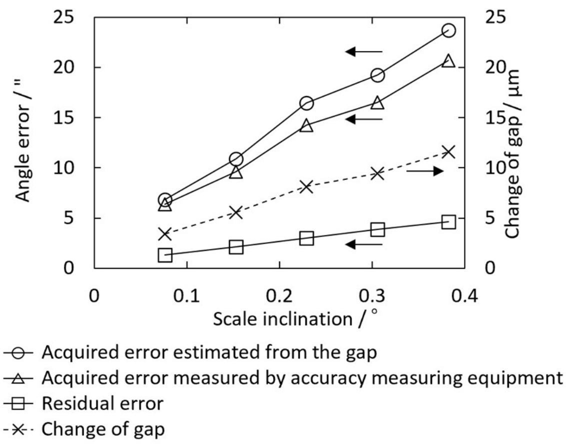

Figure 11. Peak-to-peak values of the acquired errors and the residual error for each scale inclination.

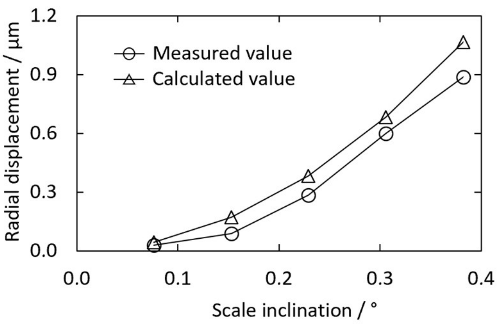

Figure 12. Maximum value of the radial displacement due to the scale inclination.