Verification of the Usefulness of Eccentric Structure in the Magnetic Encoders Using a Multipole Magnet

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It is more difficult for magnetic encoders to achieve a higher resolution than optical encoders. The resolution can be improved by multipolarizing the magnet, however the absolute angle cannot be calculated. Using the eccentric rotation of a 4-pole magnet, the authors simultaneously achieved high resolution and absolute angle calculation for a magnetic encoder. In this paper, we propose a high-resolution magnetic absolute encoder using an 8-pole magnet. The higher the eccentricity of the magnet, the easier it is to calculate the offset required to calculate the absolute angle. However, as the eccentricity increases, the angle error increases. The relationship between eccentricity and angle error is clarified, and an appropriate eccentricity is examined.

Keywords: magnetic encoder, absolute encoder, eccentric structure, multipolarization

1. Introduction

Optical encoders have been widely used. They can achieve a high resolution relatively easily, however, they are weak against dust, dirt, and oil. Therefore one of the disadvantages of optical encoders is their low performance in harsh and dirty environments. In addition, because the slit width is limited by physical restrictions, increasing the size for high resolution is inevitable. Furthermore, it is necessary to increase the size to obtain the absolute angle.

On the other hand, magnetic encoders have advantages such as low cost and, high performance in harsh and dirty environments. The magnetic encoder is classified into two: an increment type that counts the pulse train and a sinusoidal type that uses an analog signal. The increment type encoder is composed of a magnetic drum and magnetic sensors, and it converts the magnetic flux change caused by the rotation of the shaft into pulses to estimate the rotation angle. Therefore, it is impossible to estimate the absolute angle, and it is necessary to increase the number of poles to increase the resolution, resulting in an increase in size. The sinusoidal type encoder uses a sine-wave magnet which calculates the angle by using quadrature signals according to the rotation angle, similar to the resolver. Although by using a 2-pole magnet, the absolute angle can be easily obtained, it becomes difficult to increase the resolution because it depends on the signal accuracy. It has been reported that signal accuracy is improved by signal processing for higher resolution. Particularly in Refs. (7), (8), the magnet of the magnetic encoder is intentionally eccentrically attached. If the mounting accuracy of the magnet is poor, it will cause eccentricity and reduce the accuracy of the measurement. The resolution is maximized by adjusting the eccentricity of the magnet via fitting. In Refs. (9), (10), the resolution is improved by increasing the number of magnet poles. However, it is impossible to estimate the absolute angle owing to the multi-polarization of the magnet, and an additional mechanism is required to estimate the absolute angle, which leads to an increase in size.

In contrast to the existing studies where eccentric rotation of magnet is used to improve resolution, we used eccentric rotation for absolute angle calculation and high resolution. By eccentrically rotating the 4-pole magnet, a compact magnetic absolute encoder that can calculate the absolute angle without an additional mechanism realized. It has been reported that increasing the number of poles in the magnet increases the resolution. In Ref. (13), it is shown that the resolution can be improved and the absolute angle calculated by using the 4-pole magnet and the eccentric rotation. Furthermore, it has been clarified that the angle error in the angle calculation by the phase-locked loop (PLL) depends on the angle acceleration. In Ref. (14), the relationship between the mechanical angle error and quadrature signals is discussed. Eccentricity causes periodic disturbances in the signal, and this feature can be used to calculate the absolute angle. On the other hand, if the number of sensors is smaller than the number of poles of the magnet, the quadrature signals will be distorted. The distortion of the quadrature signals is directly linked to the increase of the mechanical angle error. Therefore, hall sensors for the number of poles are required.

This study has three purposes: first, to improve the resolution of the magnetic encoder with an 8-pole magnet; second, to clarify the relationship between the distortion of quadrature signals and the electrical angle caused by the converter; and third, to clarify the relationship between the eccentricity

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and the electric angle error and investigate the appropriate eccentricity.

2. Conventional Magnetic Encoders

Figure 1 shows the magnetic encoder consisting of a ring magnet and Hall effect sensors (Hall sensors for short). In Figure 1, $V_{\sin}$ and $V_{\cos}$ represent quadrature signals obtained from the Hall sensor, respectively. In the case of the 2-pole magnet, quadrature signals can be obtained by arranging the Hall elements $\frac{\pi}{2}$ rad apart. The rotation angle can be calculated from the quadrature signals obtained from the Hall sensors.

$$V_{\sin} = \sin \theta_m \quad \cdots \quad (1)$$
$$V_{\cos} = \cos \theta_m \quad \cdots \quad (2)$$
$$\theta_m = \arctan \frac{V_{\sin}}{V_{\cos}} \quad \cdots \quad (3)$$

The magnetic encoder that uses the 2-pole magnet can calculate the absolute angle. However, because the resolution depends on the accuracy of the quadrature signals obtained from the Hall sensors, it is difficult to obtain a certain accuracy.

The resolution can be improved by increasing the number of poles in the magnet\(^{(9)}\). Then, the formulae for the quadrature signals are as follows:

$$V_{\sin} = \sin \theta_e \quad \cdots \quad (4)$$
$$V_{\cos} = \cos \theta_e \quad \cdots \quad (5)$$

The formulae to calculate the electrical angle $\theta_e$ and the mechanical angle $\theta_m$ (absolute angle) are as follows:

$$\theta_e = \arctan \frac{V_{\sin}}{V_{\cos}} \left( 0 \leq \theta_e \leq \frac{\pi}{2} \right) \quad \cdots \quad (6)$$
$$\theta_m = \frac{\theta_e}{P} + \frac{2n\pi}{P} \quad (n = 0, 1, ..., P - 1) \quad \cdots \quad (7)$$

where, $P$ is the number of pole pairs in the magnet, and $n$ in Equation (7) is called the offset. According to Equation (7), it can be seen that the offset cannot be discriminated owing to the increase in the number of poles, and the absolute angle cannot be calculated. From Equation (7), the relationship between the number of poles and the maximum angle error is shown in Figure 2. The resolution of the AD converter was set to 10 bits. According to Figure 2, the resolution improves as the number of poles increases. However, compared to the case where the number of poles is increased from 4 poles to 8 poles, the improvement in measurement error is small when the number of poles is increased from 8 poles to 16 poles. Therefore, considering the disadvantages such as the increase in size due to the increase in the number of Hall sensors, this study will discuss the 8-pole magnet.

3. Magnetic Encoders With an Eccentric Structure

3.1 Overview

Figure 3 shows the structure of the proposed magnetic encoder. It consists of a multi-pole magnet and Hall sensors placed around it. An 8-pole ring magnet magnetized with a sine wave was used. The center of the magnet was mounted away from the axis of rotation. Compared to the existing studies on multipole magnets, the proposed method can realize high precision even though it has a simple structure eccentric structure, and it is easy to miniaturize. Furthermore, both the improvement in resolution and calculation of absolute angle are possible by simply making the magnet multipole, as compared with the conventional 4-pole magnet\(^{(10)}\).

Figure 4 shows the overview of the angle calculation. The magnetic flux changes $V_{\sin+}, V_{\sin-}, V_{\cos+}$, and $V_{\cos-}$ generated
by the eccentric rotation of the magnet measured by each Hall sensor are summed with the signals of the sensors arranged π rad apart to form quadrature signals.

\[ V_{\sin} = V_{\sin+} + V_{\sin-} \]  
\[ V_{\cos} = V_{\cos+} + V_{\cos-} \]  

(8)  

(9)

The electrical angle \( \theta_r \) was calculated using \( V_{\sin} \) and \( V_{\cos} \). The signals obtained from the Hall sensor are characterized by eccentric rotation for each offset section. In other words, any signal has different characteristics from the other three signals. This gives us the offset in Equation (7) by using the evaluation function based on the least-squares method. The electrical angle and the offset obtained above are combined to calculate the mechanical angle. In this way, the problem of offset cannot be specified with the increase in the number of pole—can be solved by using the eccentric rotation of the magnet.

### 3.2 Signal Characterized by Eccentric Rotation

Figure 5 shows the structure of the encoder when the mechanical angle rotates by \( \theta_m \), where \( r \) is the distance to the central axis and the face of the Hall sensors, \( r_m \) is the radius of the magnet, and \( d \) is the distance between the axis of rotation and the center of the magnet. Starting from the position \( \theta_0 \) of \( V_{\sin+} \) on the circle of radius \( r \), the positions of the respective Hall sensors \( V_{\sin+}, V_{\sin-}, V_{\cos+}, \) and \( V_{\cos-} \) are \( \theta_1, \theta_2, \) and \( \theta_3 \), respectively, where, \( \theta_0 = 0, \theta_1 = \pi, \theta_2 = \pi/8 \), and \( \theta_3 = 9\pi/8 \). Similarly, the shortest distance from the respective Hall sensors \( V_{\sin+}, V_{\sin-}, V_{\cos+}, \) and \( V_{\cos-} \) to the magnet surface is \( d_0, d_1, d_2, \) and \( d_3 \).

The eccentricity \( e \) is defined as follows:

\[ e = \frac{d}{r_m} \times 100 \]  

(10)

If the change in \( d_i \) \((i = 0, 1, 2, 3)\) is small, the output signal \( V_i \) \((i = 0, 1, 2, 3)\) of the Hall sensor can be approximated as being inversely proportional to \( d_i \) as follows:

\[ V_i = B \frac{\sin(P \alpha)}{d_i + c} \]  

(11)

where \( B \) is the amplitude of the magnetic flux density, and \( c \) is the distance coefficient determined by the characteristics of the 8-pole magnet. For convenience, we define \( \alpha \) as shown in Figure 5 to obtain \( d_1, d_2, \) and \( \sin(P \alpha) \) change with motor rotation, and \( d_i \) becomes the following from the cosine theorem:

\[ d_i = \sqrt{r^2 + d_i^2 - 2rd_i \cos(\theta_m - \theta_i) - r_m} \]  

(12)

Meanwhile the number of pole pairs \( P = 4, \sin(P \alpha) \) is as follows:

\[ \sin(4\alpha) = 4 \sin \alpha \cos \alpha \left( \cos^2 \alpha - \sin^2 \alpha \right) \]  

(13)

\[ \sin \alpha = \frac{r}{d_i + r_m} \sin(\theta_m - \theta_i) \]  

(14)

\[ \cos \alpha = \frac{1}{2d_i(d_i + r_m)} \left( d_i^2 + (d_i + r_m)^2 - r^2 \right) \]  

(15)

Therefore, the output of each Hall sensor is as follows:

\[ V_{\sin+} = V_0 = B \frac{\sin(P \alpha)}{d_0 + c} \]  

(16)

\[ V_{\sin-} = V_1 = B \frac{\sin(P \alpha)}{d_1 + c} \]  

(17)

\[ V_{\cos+} = V_2 = B \frac{\sin(P \alpha)}{d_2 + c} \]  

(18)

\[ V_{\cos-} = V_3 = B \frac{\sin(P \alpha)}{d_3 + c} \]  

(19)

### 3.3 Converter using Linear Section

As shown in Figure 6, let \( V \) be the signal with the smaller absolute value among signals \( V_{\sin} \) and \( V_{\cos} \). In other words, \( V \) can be regarded as linear with \( V_{\sin} \) and \( V_{\cos} \). \( V \) is devised into four linear intervals, as shown in Figure 6. The relationship between \( V \) and the electrical angle in each linear section is stored off-line as a look-up table. The region of the linear section of the signal \( V_{\sin} \) and \( V_{\cos} \) input to the converter is determined based on the conditions shown in Table 1. The electrical angle can be directly obtained by referring to the signal value.

![Fig. 5. Analytical model](image)

**Table 1. Summary of Sector Detector**

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Sector</th>
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<tbody>
<tr>
<td>(</td>
<td>V_{\sin}</td>
<td>&lt;</td>
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<td>(</td>
<td>V_{\sin}</td>
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<tr>
<td>(</td>
<td>V_{\sin}</td>
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</tbody>
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and electrical angle of the selected area. The look-up table can directly compensate for the imperfections of the signal obtained from the Hall sensors by utilizing the look-up table, including the phase offset, amplitude, and waveform distortion.

### 3.4 Electrical Angle Calculation Accuracy

Let $V_{max}$ be the maximum value of $V$ in each sector of Table 1. The range $R_V$ of the amplitude of $V$ is $-V_{max} < R_V < V_{max}$. Converting $V_{sin}$ and $V_{cos}$ to digital signals with an $N$-bit A/D converter (ADC for short), the relationship between the maximum value of $V_{sin}$ and $V_{max}$ is as shown in Figure 7.

\[
V_{max} : 2^{N-1} = \sin(\theta_{e}) : \sin\left(\frac{\pi}{7}\right) \quad \cdots \cdots \cdots \cdots \cdots \quad (20)
\]

\[
V_{max} = 2^{N-1} \times \sin(\theta_{e}) \quad \cdots \cdots \cdots \cdots \cdots \quad (21)
\]

\[
= 2^{N-1} \times \sin\left(\frac{\pi}{4}\right) \quad \cdots \cdots \cdots \cdots \cdots \quad (22)
\]

\[
= 2^{N-\frac{4}{2}} \quad \cdots \cdots \cdots \cdots \cdots \quad (23)
\]

Because the amplitude of each sector is $-V_{max} < R_V < V_{max}$ and there are four sectors in Table 1, the resolution $R$ of the electrical angle calculation is as follows:

\[
R = \frac{2\pi}{P \times 4 \times 2 \times 2^{N-\frac{4}{2}}} \quad \cdots \cdots \cdots \cdots \cdots \quad (24)
\]

\[
= \frac{2\pi}{P \times 2^{N+\frac{4}{2}}} \quad \cdots \cdots \cdots \cdots \cdots \quad (25)
\]

Accuracy $A$ is defined as the change in angle when the ADC changes by 1 LSB. $A$ is the maximum at the point where the slope of $V$ is minimum (the small slope indicates the magnitude of the angle change), and in Figure 7, $\theta_{e} = \pi/4$. $A$ is the reciprocal of the slope of $V$. Therefore, the reciprocal of $A$ is expressed as follows:

\[
\frac{1}{A} = \frac{d}{d\theta_{e}} \left[ 2^{N-1} \right] \times \sin(\theta_{e}) \quad \cdots \cdots \cdots \cdots \cdots \quad (26)
\]

\[
\frac{1}{A} = 2^{N-1} \times \frac{d}{d\theta_{e}} \sin(\theta_{e}) \quad \cdots \cdots \cdots \cdots \cdots \quad (27)
\]

\[
= 2^{N-1} \times \cos\left(\frac{\pi}{4}\right) \quad \cdots \cdots \cdots \cdots \cdots \quad (28)
\]

\[
\therefore A = \frac{1}{2^{N-\frac{4}{2}}} \quad \cdots \cdots \cdots \cdots \cdots \quad (29)
\]

From the above, the resolution of the encoder is improved by the resolution of the ADC and the number of poles of the magnet, and the accuracy depends on the number of bits of the ADC. Therefore, if no change in the magnetic flux density results from increasing the number of poles and the noise in the output signal of the Hall sensor is less than the resolution of the ADC, the resolution can be improved by increasing the number of poles.

### 4. Method of Offset Calculation

As described in 2, the electrical angle and the mechanical angle obtained by the converter are related by Equation (7). Equation (7) shows that when the mechanical angle is calculated from the electrical angle obtained by the converter, the mechanical angle cannot be calculated because $n$ cannot be specified. Therefore, the offset is specified using four signals characterized by eccentric rotation. It is possible to specify the offset by the following evaluation function using the least squares method.

\[
J_n = \sum_{i=0}^{3} \left| V_i - f_i \left( \frac{\theta_{e}}{P} + \frac{2\pi n}{P} \right) \right|^2 \quad \cdots \cdots \cdots \cdots \cdots \quad (30)
\]

where, $V_i$ is the signal characterized by eccentric rotation, and $f_i$ is the look-up table. The look-up table stores the relationship between the four signals $V_{sin}$, $V_{sin}$, $V_{cos}$, and $V_{cos}$ and the mechanical angle in advance offline. The sum of squares of Hall sensor output and look-up table error for all $n$ is calculated. The absolute angle can be calculated by finding $n$ that minimizes Equation (30) (If $J_0$ is less than all other $J_n$, then $n = 0$, and if $J_1$ is less than all other $J_n$, then $n = 1$...). The calculated $n$ and the electrical angle are combined based on Equation (7) to calculate the mechanical angle. Therefore, it is conceivable that the offset may not be calculated correctly owing to noise or similar causes, and a large error may occur. A solution to this problem is currently under consideration.

### 5. Evaluation of Eccentricity and Angle Calculation Accuracy

#### 5.1 Overview

There are two evaluation items in this section. First, the improvement of resolution due to the multipolarization of the magnet and to show that the absolute angle can be calculated by eccentric rotation. Second, the relationship between the eccentricity and the error of the electric angle is clarified to determine the appropriate eccentricity. The resolution $N$ of the ADC is 10 bits, and the radius of the magnet is $r_m = 10.2$.

#### 5.2 Signal Characterized by Eccentric Rotation and Angle Error

The output signals $V_{sin}$, $V_{sin}$, $V_{cos}$, and $V_{cos}$ are characterized by eccentricity, whereas quadrature signals $V_{sin}$, $V_{cos}$, and angle error are simulated by changing the eccentricity. The results are shown in Figures 8 and 9. According to Figure 8(a) and Figure 9(a), as the eccentricity increases, the difference between the maximum and minimum values of the signal increases. In addition, it can be seen that the signal amplitude changes after every cycle.

Next, the simulations of $V_{sin}$ and $V_{cos}$ during the change of eccentricity are performed, as shown in Figure 8(b) and Figure 9(b). From the signals characterized by eccentricity, it can be seen that quadrature signals for four cycles can be obtained for one rotation of the mechanical angle. On the other hand, however, waveform distortion appeared as the
Finally, we discuss the angle error. The angle errors in calculating the angle from the quadrature signals are shown in Figure 8(c) and Figure 9(c). To confirm the effect of the resolution improvement by multipolarization, we compare it with the error in the 4-pole magnet with an equal resolution of the look-up table of the converter. According to Figure 8(c) and Figure 9(c), different eccentricity has no significant effect on the angle error. The maximum angle error is approximately $4.0 \times 10^{-4}$ rad at each eccentricity, with a resolution of more than 14 bits. According to Equation (25), the resolution is approximately 14 bits when the resolution of the ADC is $N = 10$ and the number of poles $P = 4$. The simulation results show that the resolution is almost the same as the theoretical value.

5.3 Offset Calculation We perform a few simulations on offset calculation by changing in eccentricity. Figures 10 and 11 show the changes in $J_0$ with motor rotation of each eccentricity. $J_0$ is the case of $n = 0$ in Equation (30). In other words, $J_0$ is an evaluation function that determines the mechanical angle as $0 < \theta_m < \pi/2$. $J_1$, $J_2$, and $J_3$ are larger than $J_0$ at $0 < \theta_m < \pi/2$, such that it can be determined that $n = 0$. According to Figures 10 and 11, $J_0$ is smaller than other sections at $0 < \theta_m < \pi/2$.

Focusing on $J_0$ at each eccentricity, the smaller eccentricity indicates a smaller value of $J_0$. If the value of $J_0$ is small, an error in the offset calculation is likely to occur due to noise. Therefore, larger the eccentricity, the more robust the offset that can be calculated.

Figure 12 shows the offset calculated with an eccentricity of 10%. If the eccentricity is in the range of $1\% < e < 10\%$, the offset can be accurately calculated for any eccentricity. Even with an eccentricity of approximately 1%, the offset can be accurately calculated.

5.4 Relationship between Eccentricity and Angle Error The angle error and the quadrature signals at $e = 30\%$ are shown in Figures 13 and 14 to clarify the relationship between eccentricity and angle error. According to Figure 13, as the eccentricity increases, the angle error also increases. This is attributed to the fact that the quadrature signals are distorted as the eccentricity increases. As shown in Figure 14, when the eccentricity is increased, the quadrature signals are greatly distorted, resulting in an interval with a gentle slope. Figure 15 shows the angle error and the $V$ extracted from the intervals of the quadrature signals with higher linearity. As shown in Figure 15, the error increases in the interval where the slope of the $V$ is gentle (areas highlighted in light blue). Figure 16 shows the angle change per bit of the ADC for large and small slopes of $V$. According to Figure 16, when the slope is gentle, the angle change of the ADC in relation to the change in 1LSB becomes large. As a result, the angle error becomes large and the accuracy deteriorates.
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6. Conclusion

In this paper, a high-resolution magnetic encoder with an 8-pole magnet is presented. The use of a multipole magnet leads to a loss of absolute angle. The absolute angle can be calculated by using the eccentric rotation and discriminating the rotation interval from its features. Compared with the conventional 4-pole magnet, the accuracy is approximately twice as high.

By increasing the eccentricity of the magnet, the signals become more distinctive, making it easier to calculate the absolute angle. However, increasing the eccentricity leads to a deterioration in the accuracy of the quadrature signals, which directly leads to an increase in the angle error. Therefore, it is desirable to set the eccentricity to 10% or less. Reference (14) and the discussion in this paper reveal that the distortion of the quadrature signals from both the electrical and mechanical angle aspects is detrimental to angle calculation. In verification experiments involving changing the eccentricity, it is necessary to prepare several types of laboratory equipment. Therefore, in this study, we verified it only by simulation. It is desirable to conduct demonstration experiments and to establish a method where the angle error does not depend on the eccentricity in the future.

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References


Verification for Magnetic Absolute Encoders with Eccentric Structure

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