High-precision magnetic encoder module design based on real-time error compensation algorithm

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Abstract. The continuous development of industrial automation requires more and more control precision for automated control systems. As a key component of the servo motor control system, the encoder has a great influence on the accuracy of the control system. Although the common photoelectric encoder has relatively high precision, its control structure is limited by these unfavorable external environments due to its complicated structure, difficulty in integration, and vulnerability to external environments such as dust, oil, water vapor, and vibration. A high-precision magnetic encoder design based on error compensation algorithm proposed in this paper can not only effectively overcome the influence of these unfavorable conditions, but also introduces an error compensation algorithm based on ordinary magnetic encoder, which can be compared with ordinary magnetic encoder. The encoder has higher position feedback accuracy and greater stability. it can provide position information with real-time error not exceeding 0.2° within general industrial servo motor speed range. The high-precision magnetic encoder module has low cost, simple structure and easy integration, and also has considerable practical value in the field of industrial automation.

1. Introduction

As we all know, the encoder is an indispensable position sensing component of industrial servo motors. The control accuracy of the servo control system depends largely on the position feedback accuracy and stability of the encoder. Due to its high position feedback accuracy and easy to embed ABI interface on the microcontroller, the photoelectric encoder has become the position sensor of most servo motors. However, such contact type position sensing devices are often unable to work properly due to poor external conditions such as oil, moisture, dust, and mechanical vibration [1-2]. In addition, factors such as higher cost and larger size limit its market application. In contrast, as a typical representative of non-contact position sensing equipment, magnetic encoders can be harsh due to their small size, resistance to dust, oil, water vapor and other adverse conditions, vibration resistance, low cost and many other advantages. The environment has strong resistance, high work stability and low cost in the application scenario [3-5]. At present, magnetic encoders have replaced some photoelectric encoders and have been successfully applied to servo systems [6].

In recent years, many researchers have designed a variety of different magnetic encoders. In [7], Shuanghui HAO et al. designed a single magnetic pole pair magnetic encoder, which uses a calibration table lookup method to acquire the position angle information. However, the look-up table method needs to store a large amount of calibration information in the EEPROM, which consumes huge memory resources, and its calculation accuracy is also greatly limited. In the paper [8], a magnetic encoder using a fifth-order harmonic fitting algorithm was developed. It uses two pairs of Hall sensors placed opposite each other to achieve a maximum error of no more than 0.14°. Lin Q et al. [9] analyzed the various
factors of the error generated by the magnetic encoder, established mathematical expressions under different conditions, and wrote the estimation error into the ROM to realize the online compensation of the magnetic encoder error. In order to solve the error caused by mechanical installation, the error compensation table method is proposed in [10] and the cross-interval linear interpolation method is proposed to reduce the noise signal interference. It is undeniable that all of the above magnetic encoder designs have their own highlights, and both have improved the performance of the magnetic encoder to varying degrees. However, there are still problems such as insufficient analysis of the magnetic encoder error, the low efficiency of the angle solving method, and serious resource consumption.

In view of this, this paper fully analyzes the factors that cause the angular error of the magnetic encoder and specialized algorithms for different types of error factors has been proposed. Based on the error analysis, the phase compensation algorithm and the amplitude normalization algorithm are designed for the phase non-orthogonal and the amplitude inconsistency caused by the mechanical mounting error of the Hall sensors. The corresponding digital filtering algorithm is used to filter the process noise. A dynamic angle transmission delay error compensation algorithm is developed for dynamic transmission delay error. For the angle solution, considering the Coordinate Rotation Digital Computer (CORDIC) algorithm consumes small memory resources, high computational efficiency, and high-resolution accuracy [11], the CORDIC algorithm is used instead of the common look-up table method to solve the angle information. Finally, the theoretical feasibility of each algorithm is verified by simulation. The final test results also show that the proposed magnetic encoder design can not only avoid the error caused by the mechanical deviation of the Hall sensor installation, but also design the corresponding dynamics. The error compensation algorithm enables the magnetic encoder to achieve the desired measurement accuracy.

2. The overall architecture of the magnetic encoder module and the analysis of angle error

2.1. Architecture design of magnetic encoder module
As shown in figure 1, the magnetic encoder is mainly composed of signal acquisition, analog-to-digital conversion, and MCU (Micro Controller Units) processing. The analog signals induced by the four Hall sensors are converted into digital signals by a high-speed analog-to-digital converter. The reason why four Hall sensors are used is to suppress the induced error caused by temperature drift.

\[
\text{signal}1 = V_a + V_b - V_c - V_d \quad (1)
\]

\[
\text{signal}2 = V_a - V_b - V_c + V_d \quad (2)
\]

Then the converted digital signals are fed into the microcontroller (STM32F103 chip), and processed in the MCU by filtering, angle error compensation processing, and the angle calculation with the help of CORDIC algorithm, and finally the corresponding angle is output.

![Figure 1. Diagram of magnetic encoder module architecture](image)

2.2. Magnetic encoder error analysis
The error source of the magnetic encoder is mainly divided into three parts. The first part is the phase non-orthogonal and the amplitude inconsistency caused by the deviation of the mounting position of the
hall sensor. The second part is mainly caused by noise in the environment and internal electromagnetic disturbance. The third part is for specific application scenarios. For example, in servo motor applications, the motor has actually turned a certain angle from the time of signal acquisition to the final processing by the MCU. Obviously, this delay the angle is proportional to the speed of the motor. Therefore, in case of high-speed situations, the dynamic delay error cannot be ignored. These kinds of error will be analyzed deeply in the following.

![Figure 2. Position signal sensing portion of the magnetic encoder](image1)

![Figure 3. Non-orthogonal and amplitude inconsistent signals due to mounting error](image2)

2.2.1. Error caused by mechanical installation deviation
As shown in figure 2, the four Hall sensors for sensing the positional change of the rotating magnetic steel are placed at an equal distance from the axis, and the angle of the connection from each Hall transducer to axis is 90°. However, during the actual installation process, it is impossible to completely ensure that the distances of the Hall sensors from the axis are the same, and that the connection lines between the Hall and the axis are perpendicular to each other. Mechanical installation deviation causes the analog signals output by each Hall sensor to be non-orthogonal and amplitude imbalance as shown in figure 3. Suppose the phase difference of the two signals (signal 1, signal 2) is \( \phi \), and the amplitude imbalance degree between signal 1 and signal 2 is \( \alpha \) \((-1 < \alpha < 1\)). we can get the following equations:

\[
V_{signal1} = V \cdot \sin \theta \quad (3)
\]

\[
V_{signal2} = (1 + \alpha)V_{signal1} \cdot \cos(\theta + \phi) \quad (4)
\]

2.2.2. Harmonic disturbance error
Magnetic encoders are subject to interference from various noises in the environment and internal electromagnetic disturbances during operation. Figure 4 is the waveform resulting from unfiltered two induction signals. The injected harmonics will be superimposed on the real magnetic induction signal and finally fed into the MCU for operation. Obviously, the final calculation must contain errors.

2.2.3. Dynamic angle delay error
Magnetic encoder module works by continually sampling the strength of magnetic field generated by a magnet on the rotor shaft. In addition to the sampling time of the ADC, it takes a certain amount of time for the data to be processed in the MCU.
The two parts together are called propagation delays. As shown in Figure 5, by the time the magnetic encoder has converted the field strength sample into an angle calculation, the rotor will have turned for $80 \mu s$ to the position marked by the “Angle output” point. But the magnetic encoder module will tell the motor control MCU the rotor is at the “Start sampling” point. Without compensation, the motor’s commutation system cannot maximize torque because it cannot accurately capture the position information of the rotor, thereby wasting energy and reducing system efficiency. The angle of error is proportional to the speed of the rotor.

3. Algorithm design

The above error analysis illustrates that the limiting accuracy of the magnetic encoder is attributed to mounting position deviation of Hall sensors, harmonic disturbance and dynamic delay error. The high-precision magnetic encoder module proposed in this paper uses the Coordinate Rotation Digital (CORDIC) algorithm to perform the arctangent operation, and then obtains the angle information. However, in addition to the various errors introduced above, it is also necessary to design the specific error correction algorithm to improve the accuracy of the final output angle. Figure 6 is the Magnetic encoder error correction algorithm framework.

3.1. Filtering processing

We use median filtering and averaging filtering to apply magnetic field strength signals that contain ambient noise as well as internal noise interference. The median filter has a good filtering effect on the salt and pepper noise, and the mean filtering can filter the Gaussian noise in the signal. In order to achieve the desired filtering effect, we use a two-stage filtering method, first using median filtering and then using mean filtering.
As shown in figure 7(b), the harmonics are almost completely eliminated by filtering the original magnetic field strength signal containing harmonics. This result demonstrates the remarkable effect of the two-stage filtering method.

3.2. Amplitude normalization and phase orthogonalization algorithm

We design amplitude normalization algorithm and phase orthogonalization algorithm to offset the error caused by the installation error of the hall sensor.

In order to reduce the systematic error caused by the inconsistent signal amplitude, it is necessary to perform amplitude normalization processing on the signal before the angle calculation is performed on the entering system. The normalization formula is:

$$\text{out \_ signal} = \frac{(NY_{\max} - NY_{\min}) \cdot (\text{signal} - X_{\min})}{X_{\max} - X_{\min}} + NY_{\min} \quad (5)$$

Where out \_ signal is the normalized signal, NY_{\max} is the maximum value of the signal amplitude after normalization, and NY_{\min} is the minimum value of the signal amplitude after normalization. X_{\min}, X_{\max} are the minimum and maximum values of the original signal, respectively.

In order to determine whether the phases of the two signals are orthogonal, it is necessary to first calculate the phase difference from the sampled data. We use correlation analysis [12] to measure the phase difference between the two signals. Assume that the measured signals are:

$$v_1(t) = V_1 \cdot \sin(\omega t) \quad (6)$$

$$v_2(t) = V_2 \cdot \sin(\omega t - \varphi) \quad (7)$$
Where, $\varphi$ is the phase difference, $\omega = 2\pi f$, $f$ is the signal frequency. Expand equation (7):

$$v_2(t) = a \sin \omega t + b \cos \omega t$$  \hspace{1cm} (8)

Where $a = V_2 \cos \varphi$, $b = -V_2 \sin \varphi$. Then we will get the value of $\varphi$ through the following formula:

$$\varphi = \tan^{-1}\frac{-b}{a}$$  \hspace{1cm} (9)

Multiply both sides of equation (8) by $\cos \omega t$ and then integrate to get the following formula:

$$\int_{t_1}^{t_1+T} \cos \omega t \cdot v_2(t) dt = \int_{t_1}^{t_1+T} a \sin \omega t \cdot \cos \omega t dt + \int_{t_1}^{t_1+T} b \cos^2 \omega t dt$$  \hspace{1cm} (10)

Then, $a = \frac{2}{T} \int_{t_1}^{t_1+T} \sin \omega t \cdot v_2(t) dt$, $b = \frac{2}{T} \int_{t_1}^{t_1+T} \cos \omega t \cdot v_2(t) dt$. Discretize $a$ and $b$:

$$a = \frac{2}{N} \sum_{n=0}^{N-1} \sin(n\omega \Delta T) \cdot v_2(n\Delta T)$$  \hspace{1cm} (11)

$$b = \frac{2}{N} \sum_{n=0}^{N-1} \cos(n\omega \Delta T) \cdot v_2(n\Delta T)$$  \hspace{1cm} (12)

By formula (9), (11), (12), The value of the phase difference will be calculated.

3.3. Dynamic angle error compensation algorithm

In the case of a large rotor speed, the dynamic angular delay error has a non-negligible effect on the servo motor control system. From the above analysis, the delay time is a certain value, which is mainly related to the performance of the MCU and the ADC.

As long as the current rotor speed is known, the angle of the dynamic delay can be calculated from the delay time. In order to get the speed of the motor, we can perform an FFT operation on the sampled signal to obtain the frequency of the original physical signal (the voltage of the hall sensing signal). Finally, by conversion, we can get the speed of the motor. According to the Shannon sampling theorem, as long as the sampling frequency is greater than or equal to twice the effective signal frequency, the sampled value can contain all the information of the original signal, and the sampled signal can be restored to the original signal without distortion.

$$\Delta \theta = v_{\text{rotor}} \cdot T_{\text{delay}}$$
The compensation angle $\Delta \theta$ will eventually be compensated for the angular output of the module. Where the $T_{\text{delay}}$ is the sum of ADC sampling time, signal processing time and the angle calculating time. The detail duration data is shown in table 1.

| Processing | duration |
|------------|----------|
| ADC Sampling (12 bit) | 15.11 $\mu$s |
| Signal processing (STM32F103 chip) | 0.012 ms |
| Angle calculating with CORDIC | 0.198 ms |

4. Experiment and Error Validation

The accuracy verification system of the magnetic encoder is shown in figure 12.

![Figure 12. Magnetic encoder error verification experimental platform](image)

![Figure 13. Accuracy of Magnetic encoder module](image)

In order to be able to verify the accuracy of the magnetic encoder module well, a 14-bit precision photoelectric encoder is used as a reference. At the same time, we installed the magnetic encoder module we designed on the other side of the servo motor. The photoelectric encoder rotates coaxially with the magnet on the other side of the motor. In order to verify the accuracy of the magnetic encoder module we designed, we separately processed the angle data of the photoelectric encoder and the angle data of the magnetic encoder module to the PC for simple processing via RS485 Serial Communication module. We differentiate the angle information obtained from the photoelectric encoder and the magnetic encoder, and use the difference result as the angle error, as shown in the figure 13. The error result of the calibration. As can be seen from the figure, the error accuracy of the magnetic encoder at each position can reach 0.2 degree.

5. Conclusions

In order to design a high-precision magnetic encoder with high precision, simple structure, low cost and easy integration, this paper analyzes the error sources of the magnetic encoder and proposes the customized solutions based on different error factors. More importantly, an angle compensation algorithm to correct the angular error and maximize the accuracy of the magnetic encoder module has been proposed in this paper. Finally, we used a 14-bit optical encoder as a reference standard to verify the accuracy of the magnetic encoder. The experimental results show that the magnetic encoder based on the proposed design can achieve accuracy of 0.2 degrees. Compared to optical encoders, it has a longer life and lower cost. It is sufficient to replace optical encoders in certain servo motor applications.

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