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Current measurement method based on integral reconstruction of magnetic rotation angle

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Abstract: In view of the nonlinear limitation of the sine function on the magnetic rotation angle in the optical current sensor based on the light intensity detection mode, this paper proposes a current measurement method based on the integral reconstruction of the magnetic rotation angle, thus avoiding the large current measurement error caused by the approximate linear measurement of the magnetic rotation angle. In this method, the cosine term in the derivative of the sine signal containing the magnetic rotation angle is eliminated by the constant deformation of the trigonometric function, and then the magnetic rotation angle is reconstructed by integration. The experimental results show that within the current range of 0.20 Arms to 2.40 Arms, the measurement error of the current value of the integral reconstruction method is less than 1.30%, the measurement error is less than the approximate linear measurement method, and there is a good linear relationship between the magnetic rotation angle and the current, with a linearity of 99.987%.

Keywords: Current measurement method; Magnetic rotation angle.

1. Introduction

Optical current sensor , which mainly uses the Faraday magnetic rotation effect to measure the cur-rent indirectly by measuring the magnetic rotation angle. Compared with the traditional electromagnetic current transformer, the optical current sensor has the advantages of good electrical insulation, wide response frequency, no magnetic saturation and ferro-magnetic resonance. At the same time, the measured output signal can realize informatization and digitization, and has the potential to obtain current related information in real time and accurately. Therefore, optical current sensors have received extensive attention in power transmission applications.

Optical current sensor can be divided into all-fiber current sensor and magneto-optical current sensor according to different sensing units. The all-fiber cur-rent sensor [2-4] uses optical fiber as the sensing medium, improving the anti-interference ability. However, the Verdet constant of ordinary quartz optical fiber is low, and the Faraday magneto-optical rotation effect produced by it is weak. This weak effect is applicable to electrowinning, power grid and other fields involving large current. In addition, although the sensitivity of the sensor can be further improved by increasing the number of fiber turns or using special doped fiber [5-7] or photonic crystal fiber ; However, the in-crease of fiber turns will introduce additional linear birefringence and reduce its sensitivity. Excessive linear birefringence will even inhibit the Faraday effect . At the same time, the special doped fiber has the disadvantage of high loss [10, 11], which increases the cost and requires complex manufacturing technology. The magneto-optic current sensor has no effect of linear birefringence, and has simple structure and high sensitivity, especially the magneto-optic glass has high Verde constant, low absorption coefficient and other characteristics, so the magneto-optic current sensor also has good applications in weak current measurement applications such as overcurrent protection and leakage detection. However, the magneto-optic current sensor uses the light intensity de-modulation mode to obtain the information of the magneto-optic rotation angle by detecting the change of the light intensity, which leads to the approximate linear measurement of the current [12-15], which be-comes the bottleneck restricting the application of the magneto-optic current sensor. Petricevic et al. pro-posed a method for detecting the magnetic induction and current waveform of Faraday rotation using two orthogonal polarized light beams . The magnetic rotation angle is obtained by using the inverse function of the sine function. However, due to the periodicity of the sine function, the inverse function of the sine function is a multivalued function, which does not meet the requirement that an independent variable corresponds to a function value. Therefore, this meth-od is only limited to a very small magnetic rotation angle. Leonardo et al. proposed a new optical sensing technology . The voltage and current of overhead power lines are measured in real time by using the photoelectric characteristics of liquid crystal in the deformed spiral ferroelectric (DHF) mode. But the nature of liquid crystal is related to temperature. Xu et al. proposed a linear optical cur-rent sensor based on wedge crystal imaging detection . It uses a crystal wedge to convert the magnetic rotation angle into the horizontal displacement of the light and dark interference fringe, and then uses a du-al-quadrant detector to locate the fringe to realize the real-time measurement of current. Huang et al. pro-posed a linear photocurrent sensor based on a strip aluminum polarization grating, which directly con-verts the magnetically induced rotation angle into the synchronous linear motion of the light spot . How-ever, the research on the horizontal displacement or spot location of light and dark interference fringe is based on the imaging detection method to realize the linear measurement of current. The processing of op-tical devices such as coherent fiber bundles and magneto-optical films is not only difficult but also costly. At present, the research has not been able to break through the limitation of the approximate linear measurement of the magnetic rotation angle caused by the sine function in the light intensity detection mode.

In this paper, a method based on the intensity detection

mode to reconstruct the magnetic rotation angle is proposed. In this method, the derivative of the sine signal containing the angle of magnetic rotation is obtained, and the cosine term in the derivative is eliminated by the trigonometric function identity transformation. Finally, the magnetically induced rotation angle is reconstructed integrally. This can eliminate the nonlinear restriction of the sine function on the magnetic rotation angle, thus avoiding the approximate linear measurement of the current and reducing the current measurement error. In this paper, the integral reconstruction method is theoretically deduced, and the feasibility and accuracy of the proposed method are verified by building a relevant experimental platform, and the current measurement error between the integral reconstruction method and the approximate linear measurement method is compared.

2. Theoretical analysis

Faraday magneto-optical rotation effect is a physical phenomenon that magnetic field changes the properties of the medium. The principle is shown in Fig. 1. It shows that when a beam of linearly polarized light passes through a magneto-optic material placed in a magnetic field, the vibration surface of the linearly polarized light will produce a deflection proportional to the parallel component of the magnetic field (parallel to the direction of the light wave). This de-flection angle is called the magnetic rotation angle θ, which can be expressed as:

$$\theta = V \cdot \int H \cdot dL = V \cdot H \cdot L \tag{1}$$

Where V is the Verdet constant of magneto-optic material; H is the magnetic field strength; l is the length of linear polarized light passing through the magnetic field path. Since the magnetic field strength H is proportional to the current I, the measurement of current I can be realized by measuring the magnetic rotation angle θ.

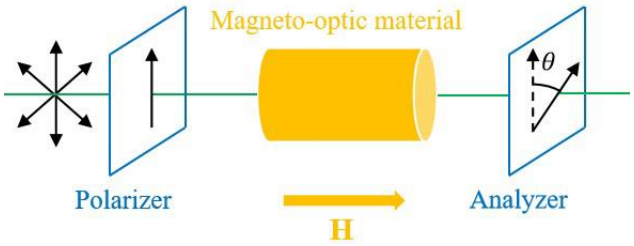


Figure 1. Faraday magneto-optical rotation effect.

Generally, magneto-optical current sensor adopts light intensity detection mode based on Marius law, and indirectly measures current by detecting the change of light intensity. When linearly polarized light passes through the analyser, the intensity of output light is:

$$I_i = I_0 \cos^2(\theta \pm \alpha) \tag{2}$$

I_0 is the incident intensity, I_i is the output strength? In order to maximize the sensitivity of the sensor, the included angle of the transmission shaft between the polarizer and the analyser α set to 45 °. Then Eq. (2) can become:

$$I_i = I_0 \cos^2(\theta \pm 45^\circ) = \frac{I_0}{2}[1 \mp \sin(2\theta)] \tag{3}$$

When the magnetic rotation angle θ<1°, the measurement of the magnetic rotation angle θ is mainly realized by the approximate linear measurement (ARM) method. It precisely controls θ and achieves approximate linearity $sin2\theta \approx 2\theta$, resulting in small dynamic measurement range and large measurement error. Therefore, in order to solve the problem of approximate linear measurement of the magnetic rotation angle, a magnetic rotation angle measurement method based on integral reconstruction algorithm is proposed. The detailed process of this method is shown below.

Because the change of light intensity cannot be detected directly, the intensity of light is converted into photocurrent by using a photodetector, and then converted into voltage by a transimpedance amplifier . Namely, the output voltage signal of photoelectric detector $U(I)$:

$$U(I) = \frac{k\eta I_0}{2} \pm \frac{k\eta I_0}{2} \sin[2\theta(t)] = U_0 \pm \Delta U(I) \tag{4}$$

Where k is the photoelectric conversion coefficient of the photoelectric detector, η is the optical path loss, I_0 is the light intensity. According to Eq. (4), the output voltage signal is composed of two parts: DC output signal U_0 and AC output signal $\Delta U(I)$. In order to make the measurement result independent of optical power and eliminate the uncertainty related to optical path change, divide the AC output signal $\Delta U(I)$ by the DC output signal U_0:

$$U = \frac{\Delta U(I)}{U_0} = \sin[2\theta(t)] \tag{5}$$

Then take the derivative of U to get the derivative of U_N:

$$U_N = U' = 2 \cdot \cos[2\theta(t)] \cdot \theta'(t) \tag{6}$$

Where U_N is the derivative of U, $\theta'(t)$ is the derivative of the magnetic rotation angle $\theta(t)$. Combining Eq. (5) and Eq. (6), $\theta'(t)$ can be obtained:

$$\theta'(t) = \frac{U_N}{2 \cdot \sqrt{(1 - U^2)}} \tag{7}$$

According to Eq. (8), the magnetic rotation angle θ (t) can be obtained by integral transformation:

$$\theta(t) = \int_0^t \theta'(t) dt \tag{8}$$

The flow structure of the integral reconstruction method is shown in Fig. 2.

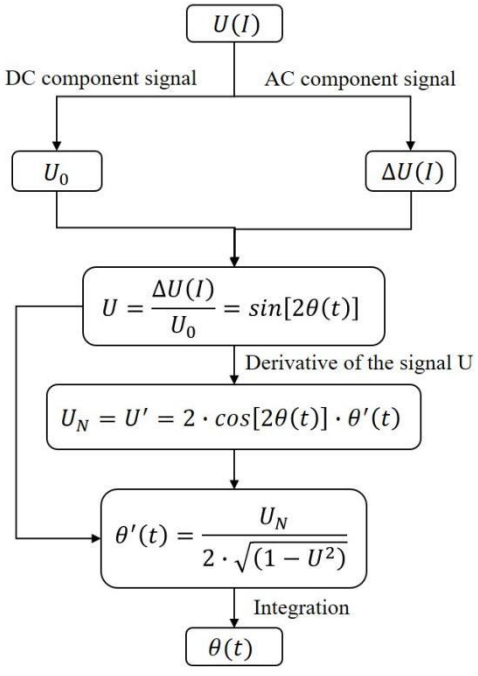


Figure 2. The flow chart of integral reconstruction method.

The excitation structure of the sensing part in this paper

adopts a multi-layer close-turn solenoid model, as shown in Fig. 3. The yellow area represents the magneto-optic glass, and the blue area represents the solenoid. Place the magneto-optic glass on the central axis inside the solenoid, and suppress the uneven distribution of magnetic field in the magneto-optic glass by designing the multi-turn coil and the length of the solenoid.

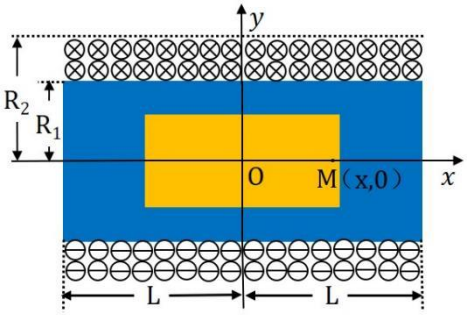


Figure 3. Cross-sectional view of multi-layer multi-turn solenoid model.

The magneto-optic glass is placed on the central axis inside the solenoid, and the uneven magnetic field distribution in the magneto-optic glass is suppressed by designing the coil and solenoid length. The inner radius of the solenoid is $R1$=7mm, the outer radius is $R2$=26.5 mm, and the length is L=32.5 mm. I is the current in the excitation coil, and the number of turns of the excitation coil is about 524 turns. According to Biot-Savard law in magnetic field , the magnetic field intensity (H) at any point M (x, 0) on the central axis of solenoid is:

$$H=\frac{NI}{4L(R_2-R_1)}\left[(x+L)\ln\frac{R_2+\sqrt{R_2^2+(x+L)^2}}{R_1+\sqrt{R_1^2+(x+L)^2}}-(x-L)\ln\frac{R_2+\sqrt{R_2^2+(x-L)^2}}{R_1+\sqrt{R_1^2+(x-L)^2}}\right] \quad (9)$$

In order to study the magnetic field distribution in the solenoid under the action of different currents, the Biot-Savart law and various parameters of the solenoid are simulated. Fig. 4 (a) - (d) shows the distribution of magnetic field intensity (H) in solenoid under different current.

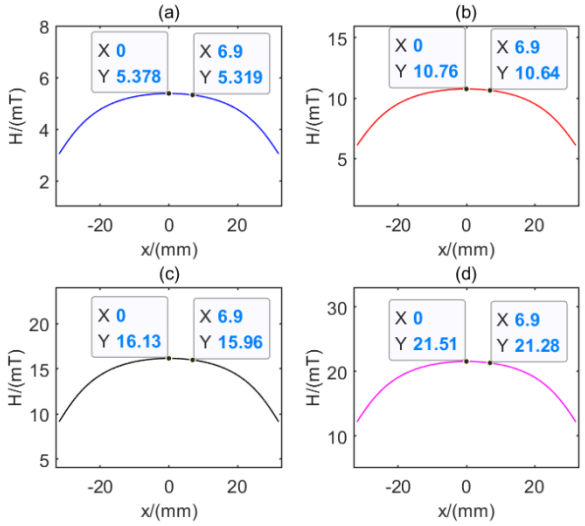


Figure 4. Simulation of magnetic field strength. (a) Current I=0.6Arms; (b) Current I=1.2Arms; (c) Current I=1.8Arms; (d) Current I=2.4Arms.

This paper simulates the distribution of magnetic field intensity H when the current I is 0.60 Arms, 1.20 Arms, 1.80 Arms and 2.40 Arms respectively. The magnetic field simulation results are shown in Fig. 4. The simulation results of magnetic field intensity show that the magnetic field intensity (H) inside the solenoid is symmetrically distributed around x=0 mm, and the magnetic field intensity gradually decreases from the centre of the solenoid to the edges of both sides. The magneto-optic material used in this paper is a cylindrical magneto-optic glass with a diameter of 3.5 mm and a length of 13.8 mm. We put the magneto-optic glass in the centre of the solenoid. Therefore, the magnetic field intensity inside the magneto-optic glass is also symmetrically distributed around the centre x=0 mm. It can be seen from the figure that the magnetic field intensity at the centre x=0 mm of the magneto-optic glass is almost equal to the magnetic field intensity at the edge x=6.9 mm, so the magneto-optic glass is in a uniform magnetic field.

3. Experiment and discussion

The structure of the experimental platform built to verify the feasibility of the integral reconstruction method is shown in Fig. 5. The experimental laser source uses a laser diode (LD) (QL65D5SA, QSI). The output power of the laser diode LD is 5.0mW and the wavelength is 650 nm. The laser diode is driven by a constant current driver (THORLABS, LD1255R). A visible collimating lens (CL) is used to convert the divergent beam output by the laser diode into a collimating beam for easy alignment. The polarizer (P) is used to change the polarization state of the out-put light of the laser diode. The magneto-optic material is the magneto-optic glass MR-4 of Xi'an Aofa Optoelectronic Technology Co., Ltd., which is represented as a cylinder with a diameter of 3.5 mm and a length of 13.8 mm. The Verde constant V of the magneto-optic glass is about 109.08 rad/(T·m) at the wavelength of 632.8 nm. Polarization beam splitter (PBS) (reflectivity>99.5%, transmission>90%, and extrapolation ratio=1000: 1) is used for polarization detection. Photoelectric detector (PD) (PDA36A-EC, Thorlabs) is used to detect light in-tensity signals, and collect data from the computer through data acquisition card (NI USB-4431) for processing and analysis. All the experimental equipment is placed on the optical isolation platform (PTR52509, Thorlabs) to avoid vibration interference from the external environment. The magneto-optic glass is placed in the centre of the excitation solenoid. The current in the solenoid coil is controlled by alternating current (AC) with a frequency of 50 Hz, and the magnetic field in the solenoid is changed by alternating current. The circuit uses a 6-bit half-high precision digital multimeter (34461A, Agilent) to monitor the current in real time.

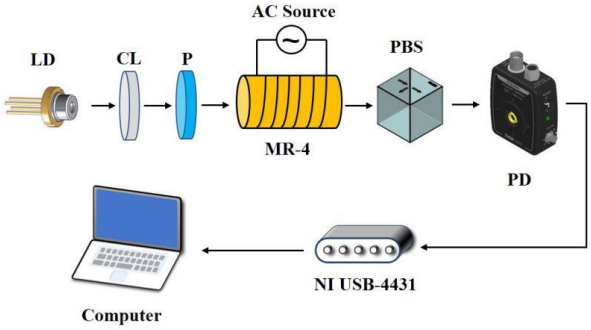


Figure 5. Experimental device structure.

Fig. 6 shows the measurement results of different effective values of 50Hz AC current. Among them, Fig. 6 (a)~(c) are the time-domain signals of magneto-optical rotation angle when the current values are 0.20Arms, 0.40Arms and 1.20Arms respectively, and Fig. 6 (d) is the corresponding spectrum. It can be seen from Fig. 6 (a)~(c) that when the

magnetic rotation angle is small, the noise signal has a greater impact on the time domain signal of the magnetic rotation angle. With the increase of current, the influence of noise signal on the time domain signal of magneto-optic rotation angle decreases gradually. Fig. 6 (d) shows a good signal to noise ratio near the signal frequency.

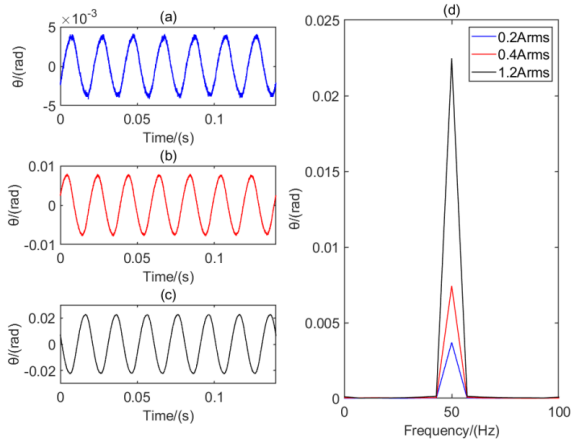


Figure 6. Measured results of 50 Hz AC current of different amplitudes. (a) Current I = 0.20 Arms. (b) Current I = 0.40 Arms. (c) Current I = 1.20 Arms. (d) Frequency domain signal.

In order to explore the measurement error of the integral reconstruction method, the experimental measurement is carried out in the range of current value I from 0.20 Arms to 2.40 Arms with 0.20 Arms as the step size. Repeat the measurement experiment for 5 times for each current measurement value. See Table 1 for the absolute measurement error and relative measurement error of different current values. The experimental results show that the absolute error of the effective value of current is less than 17 mA and the relative error is less than 1.3% in the range of 0.20 Arms to 2.40Arms.

Table 1. Measured error of current with different values.

Current values (Arms)	Absolute error (Arms)	Relative error (%)
0.20	0.0025	1.250
0.40	0.0045	1.125
0.60	0.0059	0.983
0.80	0.0082	1.025
1.00	0.0096	0.960
1.20	0.0110	0.917
1.40	0.0122	0.871
1.60	0.0134	0.838
1.80	0.0142	0.789
2.00	0.0150	0.750
2.20	0.0156	0.709
2.40	0.0164	0.683

In order to compare the error of the approximate linear measurement method (ALM) and the integral reconstruction method (IRM) on the demodulated current value, we selected six groups of experimental data with the step size of 0.40 Arms in the measurement range of the current value from 0.40 Arms to 2.40 Arms, and analysed them using the approximate linear measurement method (ALM) and the integral reconstruction method (IRM) respectively. The approximate linear measurement method (ARM) is mainly used to achieve the approximate linear measurement of current by fine control of the magnetic rotation angle ($sin2\theta \approx 2\theta$). The results of relative error analysis are shown in Fig. 7. The red line marked by a diamond is the relative error measured by the integral reconstruction method. Therefore, the blue line with an asterisk is the relative error measured by the approximate linear measurement method. The experimental results show that when the current is small, the measurement error of the integral reconstruction method is similar to that of the approximate linear measurement method. With the increase of current, the measurement error of integral reconstruction method is less than that of approximate linear measurement method.

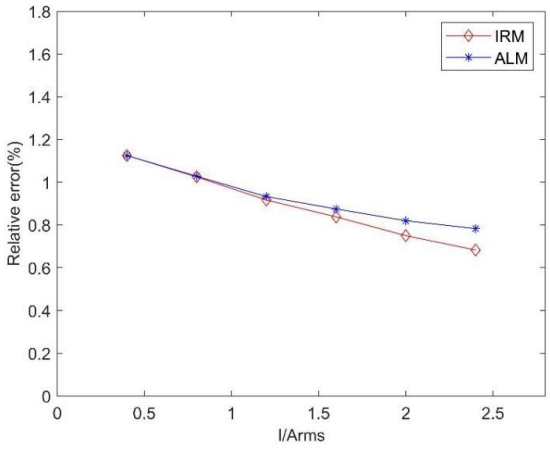


Figure 7. Comparative analysis of relative error between ALM and IRM.

In addition, according to the measurement results in Table 1, we use the linear fitting method to measure the magnetic rotation angle θ and current I, and the linear fitting coefficient is $R2$=0.99987. The fitting results are shown in Fig. 8. It can be seen from Fig. 8 that within the current value range of 0.20Arms~2.40Arms, the magnetic rotation angle θ has a good linear relationship with the effective value of current I.

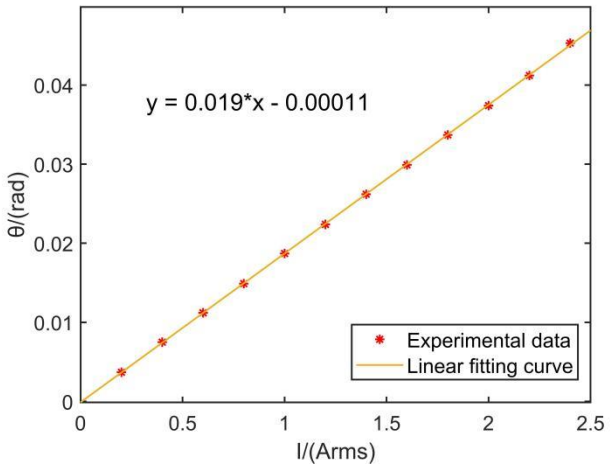


Figure 8. The linear relationship between Faraday rotation angle θ and current I.

4. Conclusion

In view of the large measurement error caused by the approximate linear measurement of the magnetic rotation angle, this paper proposes a method of integral reconstruction of the magnetic rotation angle based on the light intensity detection mode. In this method, the derivative of the sine signal containing the angle of magnetic rotation is obtained, and the cosine term in the derivative is eliminated by the

trigonometric function identity transformation. Finally, the magnetically induced rotation angle is recon-structed integrally. The theoretical analysis and experimental results show that the measurement error of the integral reconstruction method is less than that of the approximate linear measurement method, and the measurement accuracy of the current value is improved.

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