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Design of Highly Accurate and Sensitive Weak Magnetic Field Measuring Instruments Based on the Weak Magnetic Field Principle Research

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ABSTRACT
Weak magnetic field measurement is one of the important means to study the properties of matter and explore the unknown world. In order to realize high-precision weak magnetic field signal measurement, it is crucial to design an efficient signal acquisition system. Traditional magnetometers with analog output often require digital acquisition systems for analog/digital conversion, which increases the complexity of the system. To solve this problem, an innovative method based on Faraday's law of electromagnetic induction is proposed in this paper. This method cleverly converts the magnetic field strength signal into a current strength signal. Thus, it simplifies the measurement process and improves the sensitivity of the measurement. After experimental verification, the system is able to achieve a magnetic field measurement accuracy as high as 1×10^{-5} T. This fact proves the effectiveness and wide application potential of this method in weak magnetic field measurement

KEYWORDS
weak magnetic field; magnetic field signal; current signal; Faraday's law of electromagnetic induction

1 Introduction

With the development of magnetic field detection technology, weak magnetic field measurement has become one of the effective means to study the characteristics of substances and explore the unknown world. It is widely used in military and civilian fields such as underwater communication, space magnetic field detection, detection of magnetic targets in water, underwater warning and security protection, and geological exploration, and has achieved fruitful results[1]. At present, with the development and application of various new technologies and new materials, the weak magnetic field measurement technology is constantly developing and progressing. The types of magnetometers are increasingly rich, and the magnetic field measurement accuracy is also constantly improving. The measurement accuracy of commonly used fluxgate magnetometers and magneto resistive magnetometers can already reach the order of 10^{-11} T. The data storage and signal processing of this type of magnetometer need to rely on analog-to-digital converters (ADCs) to be completed, and the process is rather complicated[2]. To achieve high-precision and simple measurement of weak magnetic field signals, it is necessary to base on Faraday's law of electromagnetic induction[3]. Among them, the weak magnetic field is mainly reflected in the geomagnetic field, and there are relatively few studies to explore the geomagnetic field by cutting the magnetic field effect. Especially, the method of conducting in-depth research on the geomagnetic field by changing the resistance and adjusting the cutting distance and angle of the cutting conductor rod in the cutting loop has not been fully explored.

To fill this research gap, this study aims to conduct an in-depth exploration of the impact on the geomagnetic field by changing the resistance and adjusting the cutting distance and angle of the cutting conductor rod in the cutting loop through a combination of experiments and theoretical analyses. Advanced magnetic field measurement techniques will be adopted, combined with precise experimental designs, with the expectation of revealing the dynamic variation laws of the geomagnetic field under the effect of the cutting magnetic field and discussing the possible impacts of these changes on geophysical research. Through this study, it is expected to provide new ideas and methods for the research on the geomagnetic field and, at the same time, offer valuable references and inspirations for researchers in geophysics and related fields.

2 Construction of the model

This study explores the behavior of a conductor in a geomagnetic field[4] by cutting the current generated by the magnetic field. A high sensitivity voltmeter was used in order to measure the weak induced electromotive force. Equip an ammeter to record the magnitude of current through the conductor. Prepare adjustable resistors of different resistance values (10 Ω, 5 Ω, 1 Ω) for studying the effect of resistance on induced current. Use weights connected to a thin wire to control the falling motion of the conductor frame. Explore the current generated when the conductor cuts the magnetic field while moving in the geomagnetic field. Analyze the relationship between the current and the resistance.

The process of setting up the experimental device is as follows. The wire frame is fixed horizontally to ensure that the direction in which it cuts the geomagnetic field is perpendicular to the geomagnetic induction lines. Suspend a thin wire under the wire frame and connect it to a weight to ensure that the weight can fall freely under gravity[5]. Connect the wire frame to the voltmeter and resistance box to form a closed circuit. This process ensures that the pathway for current flow is intact so that changes in induced current can be monitored in time. With the height and weight controlled, the weights are allowed to fall freely so that the wire frame cuts the geomagnetic field. Use a voltmeter and ammeter to record the changes in electromotive force and current in real time. Stop recording after each drop and observe and record the induced electromotive force and current readings. In each experiment, adjust the resistor values (eg:10 Ω, 5 Ω, 1 Ω) and observe the changes in the induced current with different resistances.

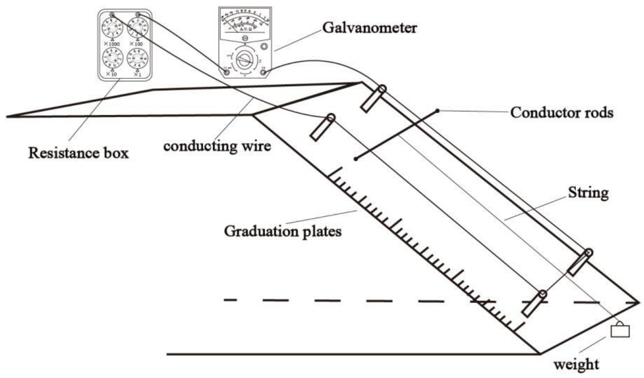

Figure 1 Experimental theory diagram

3 Experimental data measurement and analysis

An experiment is conducted with the geomagnetic field as the field source. when the cutting rod is at the starting point, the galvanometer detects a change in current. When the resistance is 10 Ω, a weak current change of approximately 5×10^{-7} A is detected. The fluctuation at 5 Ω was roughly 1×10^{-6} A. The effect at 1 Ω was roughly 5×10^{-6} A. This shows that the change in the geomagnetic field has an effect on the current. This suggests that there is a direct correlation between the magnitude of the current and the geomagnetic field, especially at specific locations. In order to accurately measure the change in current, current readings were recorded at different times thereby calculating the change in current with time. Based on the deformation and integration of the relevant formulas from the experiment, the calculation of current and magnetic field can be carried out by the following formula[6]:

$$I=\frac{d\left(B\times\frac{1}{2}\times g\times t^2\times \mathrm{L}\times\cos\theta\right)}{dt\times R} \tag{1}$$

B : is the magnetic induction in tesla (T)

A : is the effective area through which it passes, in square meters (m^2)

θ : is the angle between the magnetic field and the normal to the area

L : is the effective cutting length of the iron rod

R : is the resistance of the loop

The results of the magnetic field data when L=0.2m, T=0.4s are shown in Table 1 and 2 (current in *A*, magnetic field in *T*):

Table 1 Vertical magnetic field data results

R	i_1	i_2	i_3	B_1	B_2	B_3	$B_{average}$
10 Ω	2.6×10^{-6}	2.9×10^{-6}	2.8×10^{-6}	3.3×10^{-5}	3.8×10^{-5}	3.56×10^{-5}	3.52×10^{-5}
5 Ω	5.0×10^{-6}	6.0×10^{-6}	5.3×10^{-6}	3.2×10^{-5}	3.9×10^{-5}	3.43×10^{-5}	3.51×10^{-5}
1 Ω	2.6×10^{-5}	3.1×10^{-5}	2.4×10^{-5}	3.3×10^{-5}	3.9×10^{-5}	3.14×10^{-5}	3.45×10^{-5}

Table 2 Horizontal magnetic field data results

R	i_1	i_2	i_3	B_1	B_2	B_3	$B_{average}$
10 Ω	2.8×10^{-6}	2.3×10^{-6}	3.07×10^{-6}	3.63×10^{-5}	3.03×10^{-5}	3.96×10^{-5}	3.54×10^{-5}
5 Ω	5.4×10^{-6}	5.2×10^{-6}	5.24×10^{-6}	3.53×10^{-5}	3.37×10^{-5}	3.38×10^{-5}	3.43×10^{-5}
1 Ω	3.1×10^{-5}	2.4×10^{-5}	2.66×10^{-5}	3.89×10^{-5}	3.17×10^{-5}	3.43×10^{-5}	3.50×10^{-5}

When L=0.2 m, T=0.3 s when the magnetic field data results are shown in Table 3 and 4 (current unit is A, magnetic field unit is T):

Table 3 Vertical magnetic field data results

R	i_1	i_2	i_3	B_1	B_2	B_3	$B_{average}$
10 Ω	2.2×10^{-6}	2.1×10^{-6}	2.4×10^{-6}	3.8×10^{-5}	3.56×10^{-5}	3.87×10^{-5}	3.75×10^{-5}
5 Ω	3.9×10^{-6}	3.63×10^{-6}	4.4×10^{-6}	3.3×10^{-5}	3.12×10^{-5}	3.68×10^{-5}	3.38×10^{-5}
1 Ω	2.2×10^{-5}	1.90×10^{-5}	8.9×10^{-5}	3.8×10^{-5}	3.68×10^{-5}	3.26×10^{-5}	3.57×10^{-5}

Table 4 Horizontal magnetic field data results

R	i_1	i_2	i_3	B_1	B_2	B_3	$B_{average}$
10 Ω	2.1×10^{-6}	2.1×10^{-6}	2.0×10^{-6}	3.2×10^{-5}	3.72×10^{-5}	3.48×10^{-5}	3.49×10^{-5}
5 Ω	4.1×10^{-6}	4.6×10^{-6}	3.5×10^{-6}	3.5×10^{-5}	3.87×10^{-5}	2.96×10^{-5}	3.44×10^{-5}
1 Ω	1.8×10^{-5}	1.9×10^{-5}	2.3×10^{-5}	3.1×10^{-5}	3.22×10^{-5}	3.49×10^{-5}	3.28×10^{-5}

The data in the above table:

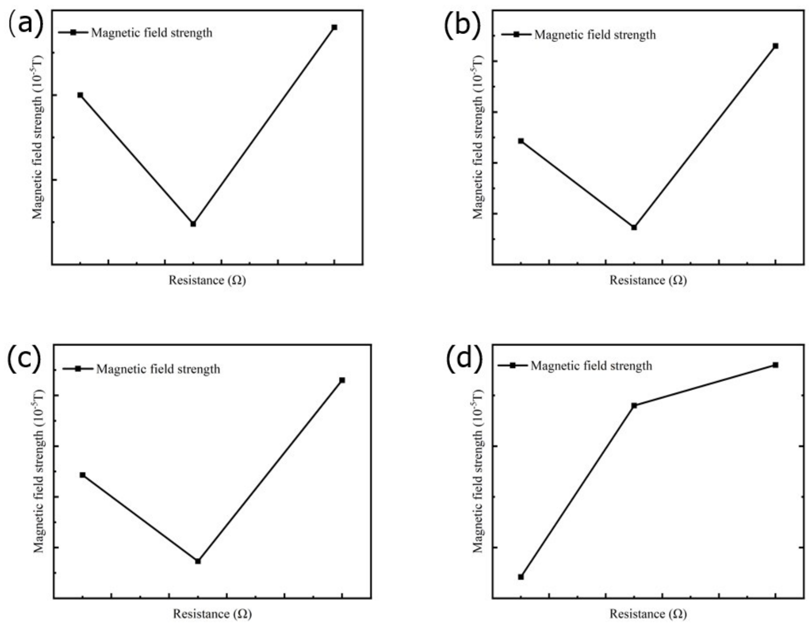

Figure 2 Experimental setup diagram

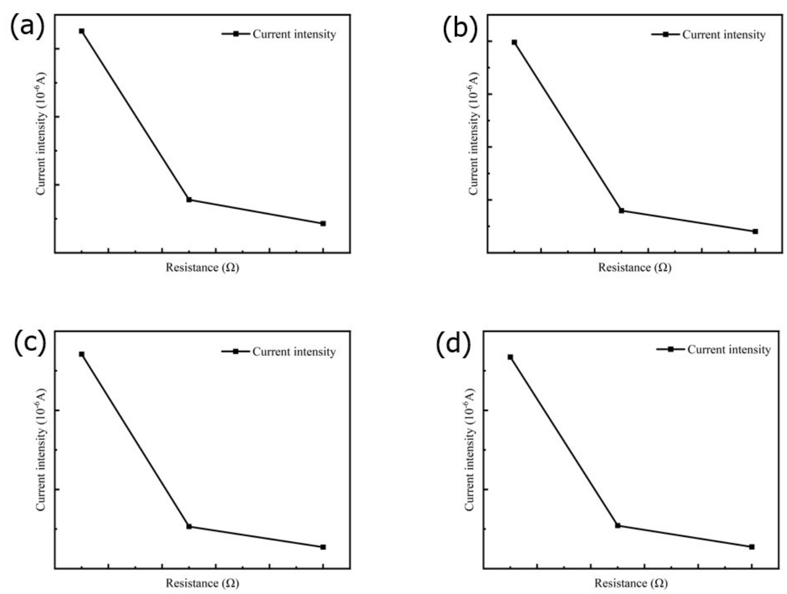

Figure 3 Current values at different resistances

In summary the horizontal magnetic field strength is: 3.7337×10^{-5}T

Vertical magnetic field strength: 3.7454×10^{-5}T

According to the Pythagorean theorem:

$$B=\sqrt{B_{level}^2+B_{vertical}^2} \quad (2)$$

The total geomagnetic field is given as: 5.28852×10^{-5} T

From the above table and combined with the uncertainty formula:

$$U=\sqrt{U_A^2+U_B^2} \tag{3}$$

Arithmetic mean formula:

$$x=\frac{\sum_{i=1}^{n}x_i}{n} \tag{4}$$

Standard deviation formula:

$$s=\sqrt{\frac{\sum_{i=1}^{n}\left(x_i-x\right)^2}{n-1}} \tag{5}$$

U_A formula:

$$U_A=\frac{s}{\sqrt{n}} \tag{6}$$

U_B formula:

$$U_B=\frac{\Delta INS}{\sqrt{3}} \tag{7}$$

Minimum index values（△INS）have 10^{-6} and 10^{-5}.

Table 5 Magnetic field uncertainty data results

R	S_i	U_A	Uncertainty of I	S_B	U_A	Uncertainty of B
10 Ω	2×10^{-7}	1.1547×10^{-7}	1.1561×10^{-7}	2.16406×10^{-6}	1.2494×10^{-6}	1.2494×10^{-6}
5 Ω	4×10^{-6}	2.3094×10^{-6}	2.3107×10^{-6}	2.06155×10^{-6}	1.1902×10^{-6}	1.1902×10^{-6}
1 Ω	1.1576×10^{-6}	6.6834×10^{-7}	6.7082×10^{-7}	1.19037×10^{-6}	6.8726×10^{-7}	6.8726×10^{-7}

Based on the results of the above experiments, it is observed that the induced electromotive force generated when cutting a magnetic susceptor in a weak magnetic field is influenced by the following key factors.

3.1 The effect of cutting angle on the induced electromotive force

In the experiment, there is a certain difference in the current intensity between horizontal cutting and vertical cutting. The cutting effect of the conductor is the best, and the induced electromotive force generated is the largest. This is because when cutting vertically, the interaction between the conductor and the magnetic induction lines of the geomagnetic field is the strongest. When the conductor in the magnetic field cuts the magnetic induction lines, the magnetic flux changes rapidly, which leads to a significant increase in the induced electromotive force. In the case of parallel cutting, the interaction between the conductor and the magnetic field lines weakens, the change in magnetic flux is less, and the induced electromotive force generated is smaller. It shows that the angle at which the conductor cuts the magnetic field lines directly determines the magnitude of the induced electromotive force.

3.2 The effect of different resistance values on the strength of the induced current

In the experiment, different resistance values were set (1 Ω, 5 Ω, 10 Ω). We then observed the changes in the intensity of the induced current under these different resistances. Low resistance (1 Ω): The experimental results show that the induced current strength is significantly higher at 1 Ω. The low resistance allows the current to pass through the conductor more smoothly and hence the current intensity is higher. Medium resistance (5 Ω): the induced current is significantly weaker. The resistance in the conductor increases, limiting the flow of current. High resistance (10 Ω): the intensity of the induced current decreases significantly. The experiment verifies the effect of resistance on the obstruction of current. The higher the resistance, the lower the intensity of the induced current.

3.3 Effect of cutting distance on the strength of induced current

In this experiment, we studied the impact of different cutting distances (0.8 m and 0.45 m) on the intensity of the induced current. Results for the cutting distance of 0.45 m. Under the cutting distance of 0.45 m, the experiment showed a relatively large intensity of the induced current. This indicates that under a shorter cutting distance, the motion change of the conductor in the magnetic field is relatively rapid. Results for the cutting distance of 0.8 m. For the cutting distance of 0.8 m, the experimental results showed that the intensity of the induced current was at an intermediate level.

The longer the cutting distance is, the longer the time for the conductor to move in the magnetic field will be. The total number of magnetic induction lines cut will be larger, and the change in magnetic flux will be more drastic. Therefore, the induced electromotive force and the induced current will be stronger. In practical applications, extending the cutting distance helps to enhance the intensity of the induced current.

4 Evaluation and Promotion of Model

This research has designed and implemented a signal acquisition system based on Faraday's law of electromagnetic induction for the high-precision measurement of weak magnetic fields. This system simplifies the measurement process and improves the signal sensitivity by effectively converting the magnetic field intensity signal into the current intensity signal. After experimental verification, we have successfully achieved a measurement precision of 1×10^{-5} T. During the research process, we have obtained the following main conclusions.

When conductors cut magnetic induction lines in weak magnetic fields, the generation of induced electromotive force is directly affected by the rate of change of magnetic flux. According to Faraday's law of electromagnetic induction, the magnitude of the induced electromotive force is proportional to the rate of change of magnetic induction lines.

Different resistance values have an obvious impact on the intensity of the induced current. As the resistance value increases, the intensity of the induced current in the conductor gradually decreases. This is because under the same induced electromotive force, a larger resistance will reduce the current-carrying capacity. Conversely, a smaller resistance will increase the intensity of the induced current. Therefore, resistance plays a crucial role in regulating the intensity of the induced current.

During the cutting process, the distance by which the conductor cuts the magnetic induction lines will also affect the intensity of the induced current. Whether it is an increase in the forward distance or an extension of the movement path, it can effectively enhance the intensity of the induced current.

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