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A Horizontal Magnetic Field Measurement Scheme Based on Helmholtz Coil Combined with Small Magnetic Needle and Projection Amplification Method

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Abstract: *A magnetic field measurement device was designed and built based on Helmholtz coils, combined with small magnetic needles and Projection amplification method. The device utilizes the geomagnetic field and two-dimensional Helmholtz coil magnetic field, combined with a small magnetic needle to indicate the direction of the magnetic field, to measure the horizontal two-dimensional component of the three-dimensional magnetic field at any point in space. During the process, use the projection magnification method to enlarge the projection for reading and reduce errors. The comparative analysis between the experimental measurement numerical calculation results obtained and the theoretical values shows that the errors are all less than 3.0%. The plan also designed devices with different accuracy and measurement ranges under different setting conditions to meet the measurement needs of magnetic fields of different intensities.*

Keywords: *Small Magnetic Needle, Projection Amplification Method, Helmholtz Coil, Magnetic Field, Biot Savart Law*

1. Introduction

The precise measurement of magnetic induction intensity is widely applied in various fields such as physical experiments, materials science, and electromagnetic environment monitoring. Currently, magnetic induction intensity measuring devices on the market, like Hall effect sensors and fluxgate sensors, although highly accurate, generally suffer from high costs, complex operations, and significant environmental impacts. These issues pose considerable challenges to experimental teaching and measurement applications, especially as the demand for low-cost, efficient measurements grows. To address these problems, we have designed and developed a magnetic induction intensity measurement device that combines small magnetic needles with light projection amplification, significantly enhancing the sensitivity and accuracy of measurements. This device not only reduces measurement costs but also offers strong ease of operation, making it suitable for a wide range of educational and industrial applications. This paper will detail the design principles, experimental procedures, and data processing of the device, showcasing its effectiveness and innovation in practical applications.

2. Experimental principle

2.1 Projection magnification method[1]

Projection magnification is a physical measurement technique that uses the principle of light propagation to amplify minute displacements or deformations, a schematic diagram of this is shown in Figure 1. Let the distance from the projection center to the object be X_1, the distance from the projection center to the projection plane be X_2, the area of the object be S_1, and the projection area be S_2. According to the principle of projection magnification, it can be specifically described as:

$$A = \frac{x_1^2}{x_2^2} = \frac{S_1}{S_2} \quad (1)$$

A is the magnification of the projection area.

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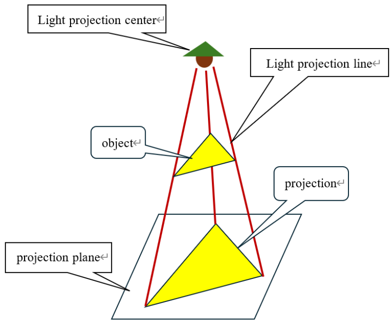

Figure 1 Schematic diagram of projection magnification

2.2 Biot-Savary law [2]

Biot-Savary's law describes the relationship between current and magnetic field. Let the current in the wire be I. The elementary magnetic field dB excited by the current element Idl is expressed by the following formula:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\times\vec{r}}{r^3} \tag{2}$$

2.3 The magnetic field of the single coil carrying current is [3]

As shown in Figure 2, a single circular coil with radius R. According to the Biot-Savary law, the magnetic field generated by a current-carrying coil with N turns on the central axis is:

$$B = \frac{\mu_0 NI}{2}\frac{R^2}{(R^2+x^2)^{\frac{3}{2}}} \tag{3}$$

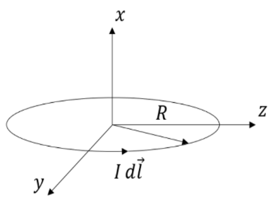

Figure 2 Circular coil coordinate diagram

2.4 Helmholtz coil magnetic field

The Helmholtz coil consists of two circular coils with a radius of R, placed coaxially and spaced equal to the radius R (as shown in Figure 3). It can generate an approximately uniform magnetic field [4]in the space between the coils. The Helmholtz coil is a symmetrical structure, and the magnetic field has symmetry, with the magnetic induction intensity of the central axis is [5]:

$$B_{(x)} = \frac{\mu_0 NIR^2}{2[R^2+(x+\frac{R}{2})^2]^{\frac{3}{2}}} + \frac{\mu_0 NIR^2}{2[R^2+(x-\frac{R}{2})^2]^{\frac{3}{2}}} \tag{4}$$

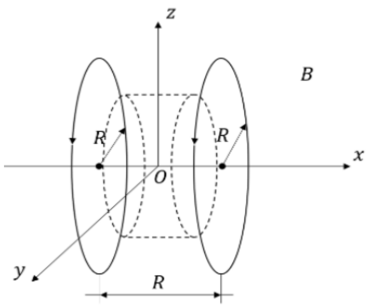

Figure 3 Schematic diagram of the Helmholtz coil

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2.5 Principle integration

A small magnetic needle deflects in a magnetic field. If multiple fields exist at the needle, it will point in the direction of the resultant vector of these fields. Place the device according to the north-south orientation of the Earth's magnetic field. A two-dimensional Helmholtz coil generates two mutually perpendicular and known magnitude magnetic fields. The coil oriented north-south is denoted as L_1, with the generated magnetic field called ΔB; the coil oriented east-west is denoted as L_2, with the generated magnetic field called B_2. Let the horizontal component of the Earth's magnetic field be B_3, and let $B_3 + \Delta B$ be B_1, which is referred to as the reinforcing magnetic field. Assume there is a weak magnetic field B "in the effective region of the coil, whose components in the directions of B_1 and B_2 are denoted as B''_1 and B''_2, respectively. Place the small magnetic needle at the geometric center of the two-dimensional Helmholtz coil. The deflection direction of the small magnetic needle gives the vector sum and direction of B_1, B_2, and B'' in the horizontal components. Since B_1 and B_2 are mutually perpendicular and have known magnitudes, only the magnitudes of B_2 need to be changed twice (denoted as $B_{2(1)}$ and $B_{2(2)}$), recording the deflection angles α_1 and α_2 of the small magnetic needle on both occasions. According to trigonometric relationships:

$$tan\,\alpha_1 = \left(B_{2(1)} + B''_2\right) / \left(B_1 + B''_1\right) \quad (5)$$

$$tan\,\alpha_2 = \left(B_{2(2)} + B''_2\right) / \left(B_1 + B''_1\right) \quad (6)$$

By combining equations (5) and (6) we obtain B''_1 and B''_2. By vectorally adding these two, we can determine the magnitude and direction of the horizontal component of the magnetic field B'' being measured. Due to the small scale of the small magnet needle, reading errors are likely to occur. Therefore, a projection magnification system composed of a point light source, a small magnet needle, and a graduated disk is used to enlarge the image of the small magnet needle onto the graduated disk for reading. This not only facilitates reading but also reduces reading errors.

In this paper, the measured magnetic field is generated by a single coil (denoted as L_3) with current, and its theoretical value is denoted as B'.

3. Design and fabrication of experimental devices

3.1 Design and manufacture of coil

The coil housing is made by 3D, and the winding wire is copper wire. The specific parameters of the coil are shown in Table 1:

Table 1 Data on coil fabrication.

Name of coil	Double coil L_1	Double coil L_2	Single coil L_3
Radius of coil (cm)	13.2	11	13.2
Number of turns in the coil	120	100	350

Note: When different measurement ranges are established, the selected coil radius and number of turns can be changed as required.

3.2 Design and manufacture of the whole device

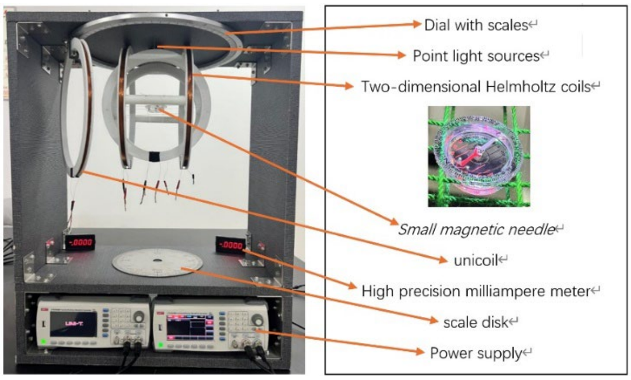

Figure 4 Physical diagram of the whole device

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The devices used in this device include: two-dimensional Helmholtz coil, single coil, scale disk, small magnetic needle, high precision milliammeter, power supply, point light source, etc., and their placement positions are shown in Figure 4

4. Empirical method

4.1 Measure the geomagnetic field B3

The instrument is placed according to the north-south direction of the geomagnetic field. The purpose of this experiment is to measure the horizontal magnetic induction intensity of the magnetic field. Although the strength of the Earth's magnetic field is not significant, it can still cause errors [6] in measurements of weak magnetic fields. Therefore, before actually measuring the magnetic field, it is necessary to first measure the strength of the horizontal component of the local Earth's magnetic field and introduce it into the experiment to reduce errors. The default orientation of the compass indicates the direction of the horizontal component of the Earth's magnetic field.

Place the small magnetic needle at the center of the inner coil, turn on the point light source, and adjust the positions of the small magnetic needle, the point light source, and the graduated disk until the projection of the small magnetic needle appears in an appropriate position on the graduated disk. Record the angle indicated by the pointer's projection at this moment. Apply current to coil L_2, gradually increasing the current while observing the angle deflection of the pointer's projection. Continue until it deflects to 45°. At this point, only the Earth's magnetic field and the magnetic field generated by coil L_2 are present at the location of the small magnetic needle, and these two fields are perpendicular to each other. Therefore, when the magnetic needle deflects 45°, according to the trigonometric relationship:

$$tan\,45° = 1 = \left(B_{L_2} \,/\, B_3\right) \tag{7}$$

That is, the horizontal component of the geomagnetic induction intensity is equal to the magnetic induction intensity generated by coil L_2. The current is denoted as i_2, and the magnetic induction intensity generated by coil L_2 can be obtained from formula (4), which is denoted as B_3. The measurement of the horizontal component of the geomagnetic induction intensity is complete. Turn off the power supply of coil L_2.

4.2 Strengthen the geomagnetic field

The strength of the geomagnetic field is slightly weaker. In the method of measuring the magnetic field with a small magnetic needle, although the magnetic field strength in the direction of L_2 corresponding to the deflection angle 0~90° is 0~∞, in practice, when the angle approaches 90°, the significant changes in the magnetic field cause very small angular changes, making the precise measurement range less than 90°. To improve measurement accuracy, we define a high-precision range for the deflection of the small magnetic needle from 30° to 60°. To increase the measurement range of the instrument, a coil L_1 is energized to generate a magnetic field reinforcement in the direction of the geomagnetic field. In this experiment, the reinforcement magnetic field is set to 10^(-3) T (the required range can be customized according to different needs, with larger ranges requiring stronger fields). We have already measured the horizontal component of the geomagnetic field, denoted as B_3. The magnetic field strength we need is B_1, so the magnetic field strength we need to produce is B_1-B_3= ΔB. From equation (4), we derive the current i_1 that generates ΔB. A constant current i_1 is applied to the coil L_1 and maintained.

4.3 Introduce the magnetic field to be measured

If there is already a magnetic field to be measured externally, simply move the small magnet needle of the instrument to the desired position. However, note that during this process, only translation is allowed; no rotation is permitted, as our previous operations were based on orientation. If there is no external magnetic field, to achieve the purpose of measuring the magnetic field, we will power the external coil L_3 to generate a magnetic field for measurement, with the current in L_3 denoted as i_3. The magnetic field to be measured is denoted as B''(the direction of B'' is horizontal). According to formula (3), we can determine the theoretical value of the magnetic field to be measured, denoted as B'. Subsequent measurements of the experimental values of the magnetic field will use this theoretical value for error calculation.

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4.4 Measure the measured magnetic field

When the test magnetic field is introduced, there are currently two magnetic fields at the small magnetic needle: the reinforcing magnetic field B_1 and the test magnetic field B ". In most cases, the small magnetic needle no longer points in the north-south direction of the Earth's magnetic field (unless the test magnetic field also points north-south like the Earth's magnetic field and the L_1 coil's magnetic field). Turn on the power supply for the L_2 coil, allowing the current to gradually increase from 0. At this point, note that the deflection angle of the small magnetic needle should increase as the current in L_2 increases. Once the small magnetic needle deflects to any angle within the high-precision range (for ease of data recording and calculation, this experiment is set to 45°), record the deflection angle and the current magnitude at this time. The deflection angle is denoted as α_1, and the current magnitude is denoted as $i_{2(1)}$. Change the current in the L_2 coil until the small magnetic needle deflects to another angle within the high-precision range (in this experiment, it is set to 60°), and record the deflection angle and the current magnitude again. The deflection angle is denoted as α_2, and the current magnitude is denoted as $i_{2(2)}$. Substitute the obtained data into formulas (4),(5), and (6) to solve for B''_1 and B''_2. Then, add the vectors of B''_1 and B''_2 to determine the magnitude and direction of the test magnetic field B''.

5. Experimental data and results

Table 2 Experimental data sheet.

Number of experiments	one	two	three	four	five	average value
Magnetic current i_2/mA	39.85	39.93	39.81	39.79	39.87	39.85
The geomagnetic field B_3/10^ (-5) T	3.26	3.27	3.26	3.25	3.26	3.26
The combined magnetic field B_1/10^ (-3)T	1					
The magnetic field is strengthened by ΔB/10^ (-4) T	9.674	9.673	9.674	9.675	9.674	9.674
Strengthen the current i_1/mA	1182.7	1182.6	1182.7	1182.8	1182.7	1182.7
L_2 coil current $i_{2(1)}$ /mA	1400.44	1401.05	1399.22	1401.30	1400.20	1400.44
L_2 coil magnetic field $B_{2(1)}$/10^ (-4)T	1.1455	1.1460	1.1445	1.1462	1.1453	1.1455
α_1	45°					
L_2 coil current $i_{2(2)}$ /mA	2615.91	2615.91	2617.50	2614.93	2618.96	2617.13
L_2 coil magnetic field $B_{2(2)}$/10^ (-4) T	2.1416	2.1397	2.1410	2.1389	2.1422	2.1407
α_2	60°					
L_3 coil current i_3/mA	1310					
The position of L_3 to the magnetic needle/cm	7					
The measured magnetic field B'/10^ (-4) T	4.3					
The direction of the measured magnetic field B	North by east 30°					

From the Table 2, we know: B_1=1 * 10^(-3) T; $B_{2(1)}$ (average) =1.1455 * 10^(-3) T; $B_{2(2)}$ (average) =2.1407 * 10^(-3) T; α_1 = 45°,α_2 = 60°. Substituting these values into formulas(5)and (6), we get B'_1=3.595 * 10^(-4) T; B'_2=2.14 * 10^(-4) T. Adding the vectors gives B'=4.1837 * 10^(-4) T, with a direction of approximately 30.764° north of east. The theoretical value of the magnetic field B' to be measured is calculated using formula (3) as B'=4.3 * 10^(-4) T (as shown in the table above).

The relative error of the size of the experimental magnetic field is:

$$\frac{B'-B''}{B'} \times 100\% \approx 2.7\% \quad (8)$$

The absolute error of magnetic field direction is 0.764°.

6. Error analysis

When recording the deflection angle of a small magnetic needle, it is an estimated reading that can easily introduce random errors, and readings are more prone to error in low-light conditions; during calculations, μ_0 represents the permeability of a vacuum medium. In reality, the permeability of air is very close to that of a vacuum but not exactly equal, leading to data errors. Objects such as the human body, power sources, and point light sources generate extremely weak magnetic fields, thus introducing

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external magnetic interference which can affect experimental results; when constructing the outer frame of the device, iron magnetic materials are inevitably used, whose permeability is very high, amplifying the magnetic field and causing errors.

7. Conclusion

The innovation of small magnetic needle combined with projection magnification method in the field of magnetic field measurement lies in its unique measurement method and significant application advantages in magnetic field measurement. The measurement system successfully achieves non-contact, high-precision, highly sensitive, and damage-free magnetic field measurements. This groundbreaking innovation provides new ideas and practical methods for magnetic field measurement techniques.

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