Original Research Article

Fabrication and Multidimensional Testing of a Spatial Micro Ampere Force Apparatus

ABSTRACT

|  |
| --- |
| This study presents a facilely fabricated spatial micro-Ampere-force apparatus, comprising two principal modules: an Ampere-force generation component and a lever-based measurement system. The apparatus measures the Ampere force via a parallelogram coil and amplifies it via lever torque equilibrium. Moreover, the Ampere force can be quantitatively monitored in real-time with a high-precision electronic balance. In practical experiments, the vertical component of the Ampere force  that this device can measure can be expressed as , and quantitative analyses have been conducted on these variable parameters. The measurement range of the apparatus is from  N to  N, coupled with a magnetic flux density sensitivity of 0.23 Gs. This instrument can be an effective pedagogical tool for electromagnetism education and a versatile experimental platform for characterizing Ampere forces, enabling multidimensional experimental exploration in secondary school physics laboratories. |

*Keywords:* *Ampere force; Lever equilibrium;* *Three-axis sensor; Magnetic induction intensity*

1. INTRODUCTION

André-Marie Ampère, the French physicist, experimentally demonstrated that a conductor traversed by electric current experiences a mechanical force when subjected to an external magnetic field—a phenomenon subsequently formalized as the **Ampere force** [1-2]. This discovery not only established a foundational linkage between electrodynamics and magnetostatics but also underpins critical operational principles in electromechanical systems, such as electric motors and generators [3-4]. In high-tech domains like maglev trains and electromagnetic railguns, the Ampere force also exerts a crucial function [5-7].

Scholars have extensively studied the design and improvement of the Ampere force apparatus. Minqiang Hu enhanced the traditional high school demonstration instrument [8]. Yang Wang quantified the relationship between the Ampere force and the angle between the magnetic field and wire [9]. Xiang Chen et al. developed a static balance method using a high-precision electronic balance to indirectly measure the Ampere force through pre- and post-power readings [10]. Yan Chen amplified the Ampere force by increasing coil turns and leveraging lever amplification [11]. Honglin Chen introduced strong thin sheet magnets and electronic scales, converting dynamic measurements to static ones and addressing issues of magnetic field doubling and leakage [12].

While existing experimental devices have improved Ampere force measurement, none can investigate the effect of the spatial angle between magnetic induction intensity and current-carrying conductors on the Ampere force. This study addresses this gap through a spatial micro-Ampere force apparatus examining coil turns, current intensity, and conductor length. The system achieves force amplification via lever equilibrium principles and multi-turn coil configurations. Featuring simplified operation and intuitive digital data acquisition, the device demonstrates sub-millinewton precision with minimized experimental errors. Its implementation in physics education enhances instructional efficacy while promoting systematic and comprehensive advancements in Ampere force measurement instruments.

2. Methodology and experimental details

**2.1 Experimental Apparatus**

Experimental instruments: Different-sized adjustable parallelogram structures composed of M4 threaded rods and M4 nuts, 0.25mm diameter enameled wire, 10×5×0.5 cm NdFeB magnet plates, custom wooden base, 3-axis wireless angle sensor, calibrated lever, counterweight iron blocks, 0.01g precision electronic balance, bubble level, circuit part: current sensor with 0.001A accuracy, DC power supply, sliding rheostat, switch, and wire.

**2.2 The Principles of Ampere Force Generation and Amplification**

Figure 1 shows the schematic diagram of the micro-Ampere-force apparatus with static moment equilibrium. When an electric current is applied to the wires on the parallelogram structure, the vertical wires on the left and right frames experience mutually cancelling Ampere force. Due to the magnetic confinement provided by the NdFeB magnetic plates, the horizontal upper-frame wires reside in a magnetic field below 3 Gs, resulting in negligible Ampere force. However, the lower-frame wires, subjected to a near-parallel external magnetic field , experience a vertically downward Ampere force. This configuration isolates the measurable force component to the horizontal lower-frame wires, enabling precise quantification of micro-Ampere forces under controlled equilibrium conditions.

图示, 工程绘图

AI 生成的内容可能不正确。

**Fig.1. Schematic diagram of the spatial** **micro-Ampere-force apparatus** **with static moment equilibrium.**

The amplification of the Ampere force in this apparatus is based on the lever amplification principle. The lower-frame wires are not subject to the Ampere force when there is no current. At this state, the lever is kept horizontal by the counterweight iron blocks combined with the fine cotton thread, satisfying the torque balance condition . When the coils are energized, the lower-frame wires are subjected to a vertical downward Ampere force . Since the cotton thread was originally in a taut vertical state, slight tension does not alter its length. Hence, the lever remains horizontal, satisfying the torque balance condition , where represents the reading of the electronic balance.

The length ratio of  and  of the apparatus is 4.344:1, which can amplify the Ampere force by 4.344 times. Additionally, by winding 50 coil-turns to equivalently enhance the current in the lower-frame wires, further amplification of the Ampere force is achieved. Thereby, even minute variations in Ampere force can induce significant changes in the balance's displayed readings.

Therefore, with , the value of Ampere force can be formulated as

 (1)

**2.3 The Experimental Principle of Ampere Force Measurement**

The expression for the spatial Ampere force is denoted as , whose magnitude is related to the magnetic induction intensity , the current  flowing through the wires, the length of the lower-frame wires, the number of coil turns , and the spatial angle between  and . This apparatus allows convenient control of the wire current  by adjusting the sliding rheostat in the circuit, with real-time current monitoring via a current sensor. It supports parallelogram structures of different sizes to adjust the lower-frame wires length  and modifies the number of turns  by varying the winding count. As shown in Figure 1, the apparatus enables horizontal angular adjustment  of the lower-frame wires via the horizontal rotation axis **Z**, and vertical angular adjustment  by altering the compression degree of the parallelogram coil structure. The aforementioned approaches can realize the multi-dimensional variable measurements of the Ampere force. As illustrated in Figure 2, since the apparatus only detects the vertical component of the Ampere force , the spatial angle is decomposed into two projections: the angle  (between the projection of the force on the **XY**-plane and the **X**-axis) and the angle  (between the force and the **Z**-axis). Consequently, the vertical component of the Ampere force acting on the lower-frame wires can be expressed as

 (2)

图示

AI 生成的内容可能不正确。

**Fig. 2.** **Schematic diagram of a parallelogram coil structure in a horizontal magnetic field.**

**2.4 Apparatus Preparation**

1) Fix the wooden structure (wooden tray, wooden stake and lever) on the base. Embed NdFeB magnet plates in the wooden tray. Wrap fine cotton thread around one end of the lever, tie a counterweight iron block to the thread and place it steadily on an electronic balance. Ensure the cotton thread remains taut and vertical during connection and calibrate it with a plumb line.

2) Use threaded rods, bolts, and nuts to fix the parallelogram structure to the other end of the lever. Attach a 3-axis angle sensor on the upper frame line of the structure. Adjust the structure's initial state to a rectangle to make the device vertical and stable. Wind the specified number of turns of enameled wires around the parallelogram structure. Balance the horizontal lever and activate the electronic balance.

3) Connect the DC power supply, single-pole switch, current sensor, and 100 Ω sliding rheostat using wires. Connect the reserved 0.25 mm enameled wire terminals to the circuit. Adjust each circuit device to the set initial value. Keep the switch open and zero the reading on the balance. For the specific physical apparatus and several parallelogram coil structures, please refer to Supplemental Material Part 1.

**2.5 Experimental Procedures**

1) Verify the linear relationship between  and: Take a parallelogram coil structure with = 50 and = 39.02 mm for the experiment. Keep  at the center of the magnetic field region, with = 0° and = 90°. Close the switch and adjust the sliding rheostat to change the current value (0.040 A - 0.250 A). Record the reading of the electronic balance each time the current is changed. Repeat this process five times.

2) Measure the  exerted on parallelogram coil structures with different  and  in the magnetic field: Replace the parallelogram coil structures and conduct the experiment with = 0.250 A, = 0°, and = 90°. Observe and record the reading of the electronic balance.

3) To measure the function relationship between  and: Keep = 0.250 A and = 90°. Before starting the measurement, place the parallelogram coil structure with = 50 and = 39.02 mm at the initial position. Rotate the structure through the horizontal rotation axis **Z** and observe the angle of the three-dimensional angle sensor on the computer in real time. Measure a point every 10°.

4) Measure the function relationship between  and: Keep = 0.250 A and = 0°. Change the inclination angle  of the structure by adjusting the compression degree. After each angle change, power off and reset the electronic balance to zero. Then power on and record the reading of the electronic balance to eliminate the error caused by the structural change. At each, change  (0 to 90°) in the manner described in (3) and record the reading of the electronic balance. More information of experimental precautions can be found in Supplemental Material Part 2.

3. results and discussion

Figure 3(a) presents the functional relationship between the Ampere force  and the current . The original measurement data can be found in Supplemental Material Part 3. By substituting the reading  of the electronic balance with  using formula (1), a linear fit was conducted on the data. The measured data shows a good linear relationship under the first-order function fitting, with an Adjusted R-Square of 0.99965, indicating the function model has high accuracy. To verify the outcome of this function, the measurement team randomly selected two currents, namely 0.071 A and 0.130 A, and respectively recorded the measurement resultsof the balance under these currents as 1.78 g and 3.26 g. The two green solid data points randomly selected correspond to Figure 3(a). It can be observed that both points are on the red fitting straight line. The relative errors between the measurement results and the values of the fitting curve are 1.74% and 1.63%, respectively, and the errors are all within 2%. It is evident that the linear variation of with exhibits a considerably high precision. The slope of this function, 0.056 ± 0.001, corresponds precisely to the partial derivative of  with respect to  in formula (2). By substituting the relevant values into the formula and converting to the International System of Units, we obtain = 0.0287 ± 0.0003 T, equivalent to = 287 ± 3 Gs.

图表

AI 生成的内容可能不正确。

**Fig. 3. (a)The relationship between the Ampere force** **and the current** **. (b) 2D magnetic field intensity profile measured in the** **-plane, where the gray area indicates the** **lower-frame wires.**

The verification of obtained through function fitting was conducted by measuring the magnetic field on the plane where is situated using a gaussmeter. Measurement data can be found in Supplemental Material Part 4, whereat each position is the average of three repeated measurements. The intuitive result of the 2D contour plotting of the data is presented as shown in Figure 3(b) above. Considering that the lower-frame wires themselves have a width of 3.47 mm and a length  of 39.02 mm. As indicated in the gray shaded area in the above figure, the magnetic induction intensity within this area is approximately 248 - 295 Gs. Hence, the fitting result of = 287 ± 3 Gs is within this range and is rather reasonable.

As detailed in Supplemental Material Part 5, the specific measurement results and analyses demonstrate that  maintains a linear dependence on both  and . The dependence of  on  and  is analyzed in detail in the following content.

图表, 图示, 直方图

AI 生成的内容可能不正确。

**Fig. 4. The** **relationship between**  **and** **, where the red solid line represents the theoretical cosine curve. (a)** **The black solid dots are the measured data from 0 to 360 degrees. (b). The three groups of data points in distinct colors represent three independent measurements.**

This paper then selected a parallelogram coil structure with = 39.02 mm and = 50 turns. Keeping the current  at 0.250 A and fixing  at 90° (i.e.,  lies in the horizontal plane), while the horizontal rotation axis **Z** is utilized to vary . The solid dots in Figure 4 represent the vertical Ampere force  experienced by the lower-frame wires at different  angles, while the red solid line represents the theoretical cosine curve. As shown in the Figure, the variation of with  follows a cosine functional dependence, approaching zero at *φ* = 90°, which aligns with the theoretical formula (2) (). However, minor discrepancies are observed between experimental data and theoretical curve in the 180°–360° range, potentially attributable to progressive instability in screw engagement of the apparatus with increasing angular displacement. Notably, near = 0° and 180° (where  is perpendicular to the magnetic field direction), measured values exceed theoretical predictions. This anomaly arises because the effective length of  decreases with increasing , while the overall magnetic induction intensity  within the *L*-occupied region increases due to the gradient magnetic field presented in Figure 3(b). Subsequently, three independent measurements were conducted as presented in Figure 4(b) to ensure the reliability of the data.

图表, 散点图

AI 生成的内容可能不正确。

**Fig. 5. (a)The relationship between**  **and** **, where the red solid line represents the theoretical sine curve and the black solid dots are the measured data. (b). The relationship between**  **and**  **under different**  **angles.**

Figure 5(a) shows the relationship between  and with =0°, where the black solid dots are the measured data. Owing to the parallelogram structure's geometric constraints and material properties, seven different angles were measured with the minimum inclination angle limited to 53.7°. During the vertical inclination angle  variation, the Ampere force  as a function of  approximately follows a sinusoidal trend, as shown in Figure 5(a) (i.e., ). However, due to the non-uniformity of the magnetic field, the experimental data points slightly deviate from the theoretical red sine curve. Subsequently, the variation of force  with angle  was measured from 0°to 90°at three different inclination  angles. The normalized results are shown in Figure 5(b) above. For any fixed , the dependence of  on  generally follows a cosine function trend. Minor discrepancies have been discussed in the previous paragraph, but the overall behavior confirms that the apparatus satisfies.

Finally, the measurable range and sensitivity of the Ampere force  for this apparatus are discussed. The upper limit of the current  flowing through the wire is 0.250 A, while the lower limit can be adjusted to 0.001 A via a sliding rheostat. When = 0.001 A, the corresponding force . Considering the measurement resolution of the electronic balance is 0.01 g, the minimum detectable change in the theoretical Ampere force is determined by the precision of the balance. Specifically, since the balance can resolve mass changes as small as 0.01 g, the lower limit of measurable force is.At the upper current limit = 0.250 A, the force reaches  based on the earlier linear fitting formula. Whenchanges by 0.01 g, the corresponding force variation is . Assuming all other parameters remain constant, the sensitivity of the apparatus to changes in the ambient magnetic induction intensity is conducted as .

4. Conclusion

In this paper, a multi-dimensional experimental apparatus is designed for measuring spatial micro-Ampere force. The system experimentally investigates the effects of current , turns , lower-frame wire length, and spatial angles  and  on the Ampere force . Experimental results confirm the relationship , with measured deviations in  relative to remaining within 2%. The measurable range of  spans from to , and the apparatus achieves a sensitivity of 0.23 Gs for detecting spatial magnetic induction intensity variations. In educational contexts, this instrument serves as an intuitive teaching tool to help students visualize factors influencing Ampere forces. It also enables multidimensional inquiry-based experiments for secondary school students, bridging theoretical knowledge and practical operations.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

References

1. Hofmann JR. (1987). Ampère’s Invention of Equilibrium Apparatus: A Response to Experimental Anomaly. *The British Journal for the History of Science*, 20(3),309-341.
2. David Halliday, Robert Resnick, Jearl Walker. (2013). Fundamentals of physics. *John Wiley & Sons*.
3. Calvert J F. (1931). Forces in turbine generator stator windings. *Transactions of the American Institute of Electrical Engineers*, 50(1), 178-194.
4. Boldea I. (2017). Electric generators and motors: An overview. *CES Transactions on Electrical Machines and Systems*, 1(1), 3-14.
5. Dong, F., Hao, L., Park, D., Iwasa, Y., Huang, Z. (2023). On the future sustainable ultra-high-speed maglev: An energy-economical superconducting linear thrusting system. *Energy Conversion and Management*, 291, 117247.
6. Graneau P. (1982). Application of Ampere’s force law to railgun accelerators. *Journal of Applied Physics*, 53(10), 6648-6654.
7. Liu L, Zhang X, Wang J. (2023). Dynamic Response and Parameter Analysis of Electromagnetic Railguns under Time Varying Moving Loads. *Shock and Vibration*, 2023(1), 4351878.
8. Minqiang Hu. (2006). Design and Experimental Research of Quantitative Demonstration Device for Ampere Force. *Physical Experiment*, (06), 26-30. Chinese.
9. Yang Wang. (2022). Quantitative Exploration of the Relationship between the Ampere Force on a Current-Carrying Conductor and the Angle between the Magnetic Field and the Conductor. *Middle School Physics Teaching Reference*, (20), 58-60. Chinese.
10. Xiang Chen, Shihua Xue, Zhongqiu Hu, Yan Liu. (2019). Principle and Demonstration Instrument Making of Measuring Ampere Force by Static Balance Method. *Journal of Neijiang Normal University*, 34(12), 82-85. Chinese.
11. Yan Chen. (2015). Improvement of Quantitative Experiment for Exploring the Magnitude of Ampere Force. *Teaching Instruments and Experiment*, 31(9), 40-42. Chinese.
12. Honglin Chen. (2021). Improvement of Experiment for Exploring the Magnitude of Ampere Force. *Middle School Physics Teaching Reference*, 50(2), 42-44. Chinese.