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Measurement of Earth's Magnetic Field Using a Tangential Magnetometer

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ABSTRACT The study of Earth's magnetic field has been of great importance in recent years due to solar storms that affect it and the functions that depend on it. This report presents an experiment in which, using a coil, a compass, a power supply, and a resistor, Earth's magnetic field is obtained at the location of Universidad del Valle de Guatemala (Latitude: 14.6017° N, Longitude: -90.4878° W). It was determined that this value was 35.4 $\pm$ 0.9 μT, thus obtaining a percentage error of 4.07% when compared to the theoretical value. The main sources of error were due to the coil dimensions, winding, and system instability, so the use of a coil winding machine and a variable capacitor is recommended to obtain better results.

INDEX TERMS Biot-Savart Law, RL Circuit, Magnetic Needle

I. CONCEPTUAL FRAMEWORK

A. INTRODUCTION

Earth's magnetic field has been the subject of recent study, especially due to anomalous solar storms that have affected our planet. This magnetic field protects us from such storms, so there is no reason for alarm. However, it is important to note that its magnitude and direction are not constant, as they can vary due to the same solar storms. Therefore, its study in different geographical areas and at different times of the year is of great interest to fields such as telecommunications, navigation, and physics.

Earth's magnetic field varies between $30\mu T$ and $70\mu T$. This report proposes a practical experiment to measure Earth's magnetic field using a coil, a compass, and simple electronic equipment. The results obtained were compared with data available on the website `magneticdeclination.com`[**magnetic-declination**]. This report was inspired by work done by Sosa et al. at the University of Guanajuato [**sosa2003tangent**].

B. THEORETICAL MODEL

1) Magnetic Field of a Circular Coil

We wish to calculate the magnitude and direction of the magnetic field B on the axis of a circular coil of radius R carrying a current I [**lorrain1982magnetic**].

An element Idl of the current produces a magnetic induction dB. By symmetry, the magnetic induction will be along the axis and

$$dB_z = \frac{\mu_0 I dl}{4\pi r^2}\cos(\theta) \tag{1}$$

Then, integrating, considering that the length goes from 0 to R, we obtain:

$$B_z = \frac{\mu_0 I 2\pi R}{4\pi r^2}\cos(\theta) \tag{2}$$

It is known from trigonometry that:

$$\cos(\theta) = \frac{R}{r} \tag{3}$$

Since

$$r = \sqrt{R^2 + z^2} \tag{4}$$

Then, substituting (3) and (4) into (2), we obtain:

$$B_z = \frac{\mu_0 I R^2}{2(R^2 + z^2)^{3/2}} \tag{5}$$

Being N the number of turns and C the number of layers of the coil, the magnetic field of the coil can be determined as:

$$B_z = \frac{\mu_0 CNI}{2}\frac{R^2}{(R^2 + z^2)^{3/2}} \tag{6}$$

2) Measurement of Earth's Magnetic Field

A very simple way to measure Earth's magnetic field B_t is using a coil and a magnetic needle. Knowing that a magnetic needle within a magnetic field B_b will deflect in the direction of the resulting field, and calculating the angle θ formed by the needle and Earth's magnetic field, whose relationship is:

$$\tan(\theta) = \frac{B_b}{B_t} \tag{7}$$

Since the value of the magnetic field is derived from the tangent function, this device is commonly known as a *tangent magnetometer* or *tangential magnetometer*.

C. ASSUMPTIONS

- The magnetic permeability of MDF is the same as that of vacuum.
- The coil layers are connected in series.
- The addition of glue is minimal and does not affect the magnetic permeability or the dimensions of the coil, as well as the electrical tape.

II. OBJECTIVES - HYPOTHESIS

A. OBJECTIVES

- Design and build a coil that allows generating a uniform magnetic field.
- Obtain the tangent of the angle at which the magnetic needle deflects and compare it with the magnetic field generated by the coil.

B. HYPOTHESIS

- The relationship between the magnetic field generated by the coil and the tangent of the deflection angle of the magnetic needle should be linear with respect to the increase in supplied voltage.

III. MATERIALS AND METHODS

A. MATERIALS

- 3 MDF boards 30x40cm.
- Wooden rods 30 cm long
- 50 meters of 28 AWG magnet wire
- 50 milliliters of wood glue
- Brush
- Electrical tape
- 1 Alligator-alligator cables
- 2 Alligator-banana cables
- 1 50 ohm power resistor
- 1 Magnetic needle (Compass)
- Sandpaper
- BK Precision 1760A power supply with capacity from 0 to 38V

B. METHODOLOGY

The experiment setup begins by cutting 12 MDF rings with an outer diameter of 13.5 cm and an inner diameter of 9 cm, using a laser cutter. Subsequently, the rings are glued one on top of the other with wood glue, applying it with a previously moistened brush to prevent the glue from drying. Then, the winding is done very carefully, ensuring that each wire is well aligned with the previous one. Up to two layers of winding may be necessary, each secured with electrical tape. It is crucial to leave a wire 1 meter long at each end of the coil. Then, 5 centimeters at each end are sanded to remove the enamel, and electrical tape is placed behind the sanded area. Next, the base is mounted by cutting four MDF boards with specific dimensions[1] and dividing six wooden rods into six 12 cm rods and six 18 cm rods, which are glued with wood glue to create two bases: one for the coil and one for the compass, ensuring that the compass is centered inside the coil. Then, the coil is inserted into the large base and the small base inside it, placing the compass on top of the small base. It is essential that both the coil and the compass are aligned in the north-south direction of the magnetic field at the geographical location of the experiment. Subsequently, one end of the coil is connected to a resistor using alligator cables and the other end directly to the power supply (ground connection). Measurements proceed, starting with a voltage of 1.5 volts and increasing in increments of 0.1 volts up to 2.5 volts (this may vary depending on the current the coil allows). During each measurement, the voltage, current, and deflection angle of the magnetic needle are recorded. The current can be measured with the power supply, but if it does not have a current meter, a multimeter can be used connected between the ground connection and the power supply. It is important to keep the power supply on during the entire process and not disconnect it between measurements.

C. DIAGRAM

Power supply.png

Figure 1: System

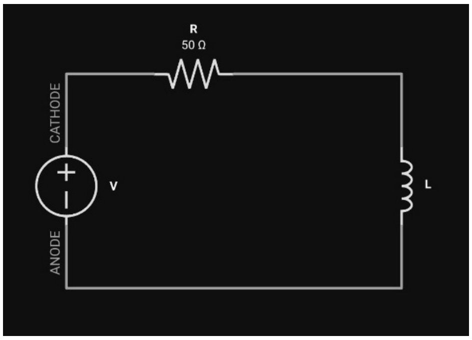

Figure 2: Circuit

D. CONSTANT DATA

- Resistance = 50 ohms
- Magnetic permeability = $4\pi \times 10^{-7}\ \frac{H}{m}$
- Number of turns = 115
- Number of layers = 1.75
- Outer radius of coil = 6.75 cm.
- Inner radius of coil = 4.5 cm.
- Magnet wire diameter = 0.321 mm.

[1] https://drive.google.com/drive/folders/12ZuJ4J0rxn5OBgtGgTfiL6sGyhQp3mD0?usp=sharing

IV. RESULTS

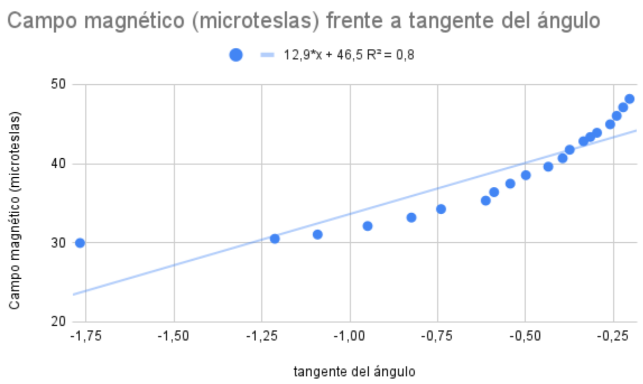

Figure 3: B_b vs. $tan(\theta)$ (20 data points)

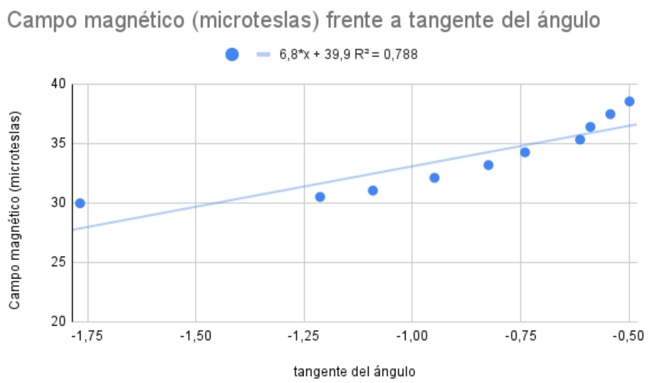

Figure 4: B_b vs. $tan(\theta)$ (First 10 data points)

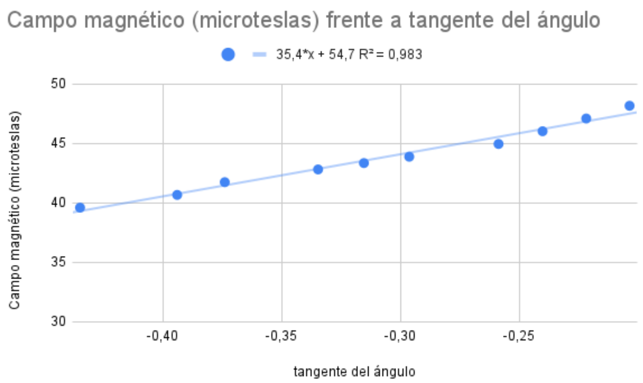

Figure 5: B_b vs. $tan(\theta)$ (Last 10 data points)

Voltage (V)	Current (mA)	Angle (°)	$B_b(\mu T)$
1.50	27.0	244	28.90
1.55	28.0	241	29.97
1.60	28.5	231	30.51
1.65	29.0	228	31.04
1.70	30.0	224	32.11
1.75	31.0	220	33.18
1.80	32.0	217	34.25
1.85	33.0	212	35.32
1.90	34.0	211	36.39
1.95	35.0	209	37.46
2.00	36.0	207	38.53
2.05	37.0	204	39.61
2.10	38.0	202	40.68
2.15	39.0	201	41.75
2.20	40.0	199	42.82
2.25	40.5	198	43.35
2.30	41.0	197	43.89
2.35	42.0	195	44.96
2.40	43.0	194	46.03
2.45	44.0	193	47.10
2.50	45.0	192	48.17

Table 1: Results for current, angle and magnetic field.

V. DISCUSSION

Three tests were performed to determine Earth's magnetic field. In the first test, the voltage was varied from 0.1V to 3V in increments of 0.1V, but it was done without a resistor, resulting in a current that ranged from 50mA to 811mA. This generated a deflection close to 180 degrees in each measurement, with almost imperceptible changes. The resulting graph had a coefficient of determination (R^2) of 0.32.

In the second test, a 50 ohm, 10 watt resistor was used to reduce the current. The voltage was varied between 1.5V and 2.5V in increments of 0.1V, obtaining a current that ranged from 27mA to 45mA. This time, the R^2 was 0.746, indicating an adequate current range.

In the third test, the previous procedure was repeated varying the voltage between 0.05V and 0.05V, from 1.55V to 2.5V. The current varied between 28mA and 45mA. An R^2 of 0.8 was obtained in the 20 measurements (figure 3). However, when dividing the measurements into two groups, the first 10 (1.55V-2V) obtained an R^2 of 0.788 (figure 4), while the last 10 (2.05V-2.5V) reached an R^2 of 0.983 (figure 5). This suggests that the adequate range for measuring the magnetic field is in the last interval.

The discrepancy between the results of the first and last 10 data points is due to the time it takes for the coil to receive current when turned on. The first measurements are more influenced by resistance, which is reflected in the initial curve of figure 3 before stabilizing.

Earth's magnetic field was determined as the slope of the graph in figure 5, being 35.4 $\pm$ 0.9 μT. When compared to the value obtained from $magneticdeclination.com$ (36.9μT), an error of 4.07$\%$ is obtained.

Despite not achieving to measure the uniformity of the magnetic field generated by the coil, the objective of designing and building one was fulfilled. Its linearity was verified in the range between 2.05V and 2.5V, confirming the stated hypothesis.

The main sources of error were the dimensions and winding of the coil. It is recommended to increase the coil diameter to more than 13.5 cm and use a winding machine to improve field uniformity. Additionally, it is suggested to change the RL circuit to an RLC circuit, with a capacitor in series, to stabilize the charge and avoid measurements influenced by resistance.

VI. CONCLUSIONS

- The design of an RLC circuit with some variable capacitor or varicap would allow greater stability to the system, thus reducing the difference between results.
- A linear relationship was observed between the magnetic field generated by the coil and the tangent of the angle in the range between 2.05V and 2.5V, thus obtaining an Earth's magnetic field of 35.4 $\pm$ 0.9 μT.

VII. ACKNOWLEDGEMENTS

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