Magnetic Fields

Nolan Tremelling

October 12, 2023

Abstract

An experimental process to determine the strength of a magnetic field in the gap of an electromagnet through observation of closed loop induced EMF.

1 Introduction

This experiment utilizes two techniques for measuring the strength of a magnetic field, $\vec{B}$. One approach utilizes the deflection force a current-carrying conductor feels in a magnetic field and the other exploits Faraday's Law and measures the EMF induced by a varying magnetic field in a closed loop.

1.1 Force on a Current-Carrying Conductor

For a wire or rod of length $\vec{L}$ carrying a current i, placed in a magnetic field $\vec{B}$, it experiences a force:

$$F = i\vec{L} \times \vec{B} \quad (3.1) \tag{1}$$

If $\vec{B}$ and the current are perpendicular, the force is then:

$$F = iLB \tag{2}$$

By knowing the current i and the force F, the magnetic field strength, B, is found.

1.2 EMF Induced in a Moving Coil

For a closed conducting loop of area A in a magnetic field $\vec{B}$, the magnetic flux through the loop is given by:

$$\Phi = \int \vec{B} \cdot \hat{n} dA \tag{3}$$

When $\vec{B}$ is perpendicular to the loop's plane, this simplifies to:

$$\Phi = BA \tag{4}$$

Faraday's Law states that if this flux changes over time, an EMF ε is induced:

$$\varepsilon = -\frac{d\Phi}{dt} = -\frac{d(BA)}{dt} \tag{5}$$

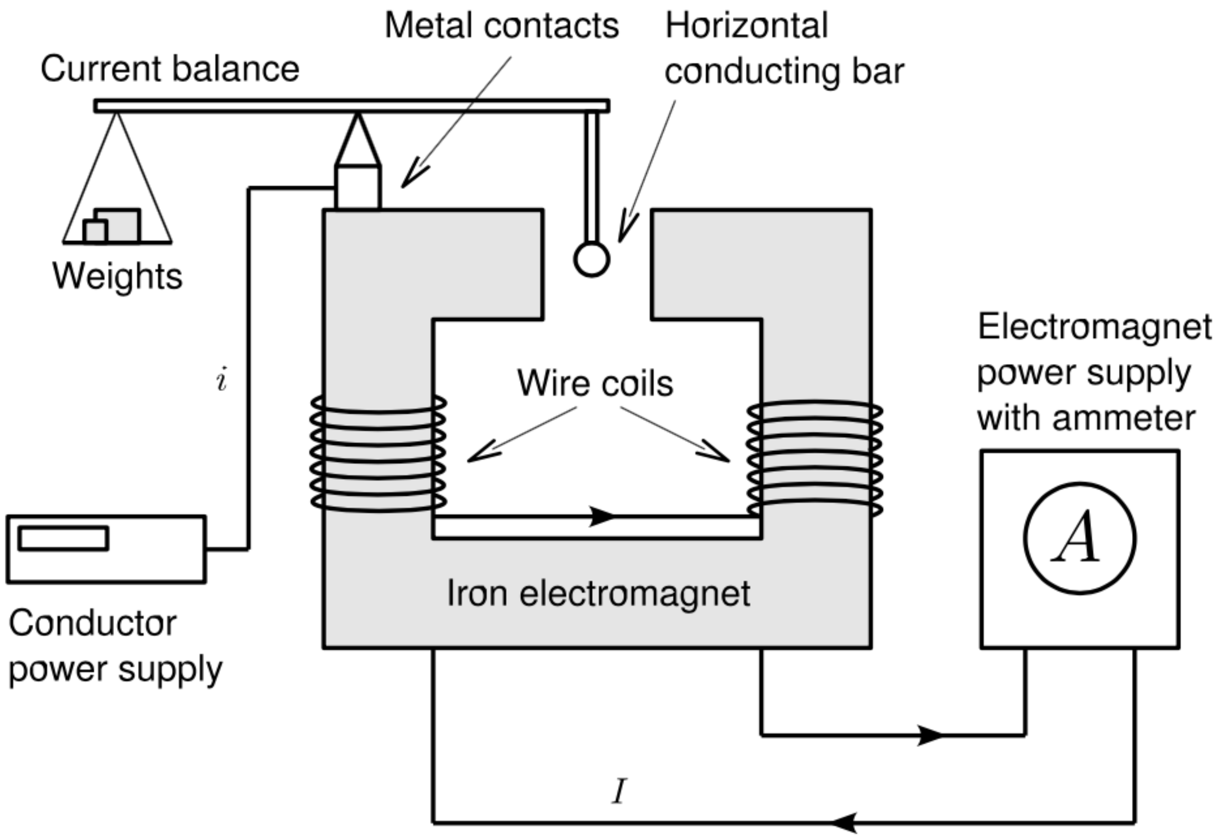

Figure 1: Setup of the wire, magnet, and balance for force measurement.

And so for a coil with N loops:

$$\varepsilon = -N\frac{d\Phi}{dt} \quad (3.2) \tag{6}$$

Measuring ε can helps in determining the magnetic field strength.

2 Method

In the first part of the experiment, a current balance is set up, as shown in Figure 1. To estimate the strength of the electromagnet, the magnetic force exerted on a horizontal current carrying rod is used. The electromagnet provides the magnetic field for this experiment and the magnitude of this magnetic field is directly proportional to the current flowing through it, where there is a constant of proportionality dictated by the geometry of the setup.

Here, B is generated within the air gap of a C-shaped electromagnet. This electromagnet is characterized by numerous coils wrapped around an iron core. An adjustable low voltage power supply provides the necessary current, I, to the electromagnet. Once a magnetic field B is established in the electromagnet, adjusting the current i in the rod allows for manipulation of the force exerted on the rod. To gauge the magnitude of this force, a balance is used. By using a series of weights, the balance is then calibrated to achieve equilibrium. Once this equilibrium state is attained, the gravitational force acting on the weights, represented by $F = mg$, is equivalent to the magnetic force acting on the conducting rod.

Alternatively, the principles of Faraday's law can be used for measuring B. Such an experimental setup consists of a rotary motion sensor fixed to the end of a cross-rod. This sensor also serves as a pivot for the induction wand. Designed as a rigid pendulum, the induction wand has a coil at its tip that is designed to swing through a variable gap magnet. When this coil is abruptly inserted into, or extracted from, the magnetic field, there is a swift alteration in the magnetic flux through the coil. This, in turn, induces an electromotive force (ε). As long as the rate of change of the magnetic flux ($\frac{d\Phi}{dt}$) is not zero, ε drives a current (i) through the coil.

For the experimental setup used here, the coil comprises $N = 200$ turns, and it has an outer diameter of $d = 3.1$ cm. As the coil traverses the gap between the magnets, it moves from an area with zero magnetic field (external to the gap) to an area with a non-zero field (at the gap's center). This movement induces an EMF in the coil.

3 Results and Discussion

Conducting both experiments generates a significant amount of data. Two interesting plots can be generated from this data, the plot of iL against $F = mg$, and the plot of the magnetic field B against I.

The plot of plot of iL against $F = mg$ is seen in Figure2. From this graph we observe that there is a linear relationship between iL and $F = mg$, where the value of F consistently increases with the value of iL. This highlights a strong relationship between the two quantities, and implies that the strength of a magnetic field, B is directly proportional to its current.

Figure 3 shows the plot of the magnetic field B against I. This analysis utilizes Faraday's Law of Electromagnetic Induction. We see that when the coil

When the coil enters the magnetic field, we saw a spike in the magnetic flux through the coil, and when it left the field a change in the opposite direction. This was observed but not captured to report. The sign of the induced EMF is determined by the direction of the change in magnetic flux. As the coil enters the magnetic field, the flux increases and induces an EMF in one direction. As the coil exits the field, the flux decreases, inducing an EMF in the opposite direction. This is consistent with Lenz's law, which states that the direction of the induced EMF will always be such as to oppose the change in flux that produced it. When the coil is at the exact center of the magnet, it is fully within the magnetic field, and there's no change in the magnetic flux through the coil. This leads the rate of change to be zero at the center, therefore the induced EMF is also zero.

4 Conclusion

This experiment explored two distinct methodologies to ascertain the strength of a magnetic field, $\vec{B}$. Both methods provide insight into the relationship between various parameters affecting the strength and behavior of the magnetic field.

From the current balance experiment, a clear linear relationship was identified between the product of the rod's current and its length (iL) and the gravitational force acting on the rod ($F = mg$). This relationship reinforces the idea that the strength of a magnetic field, B, is intrinsically tied to its current.

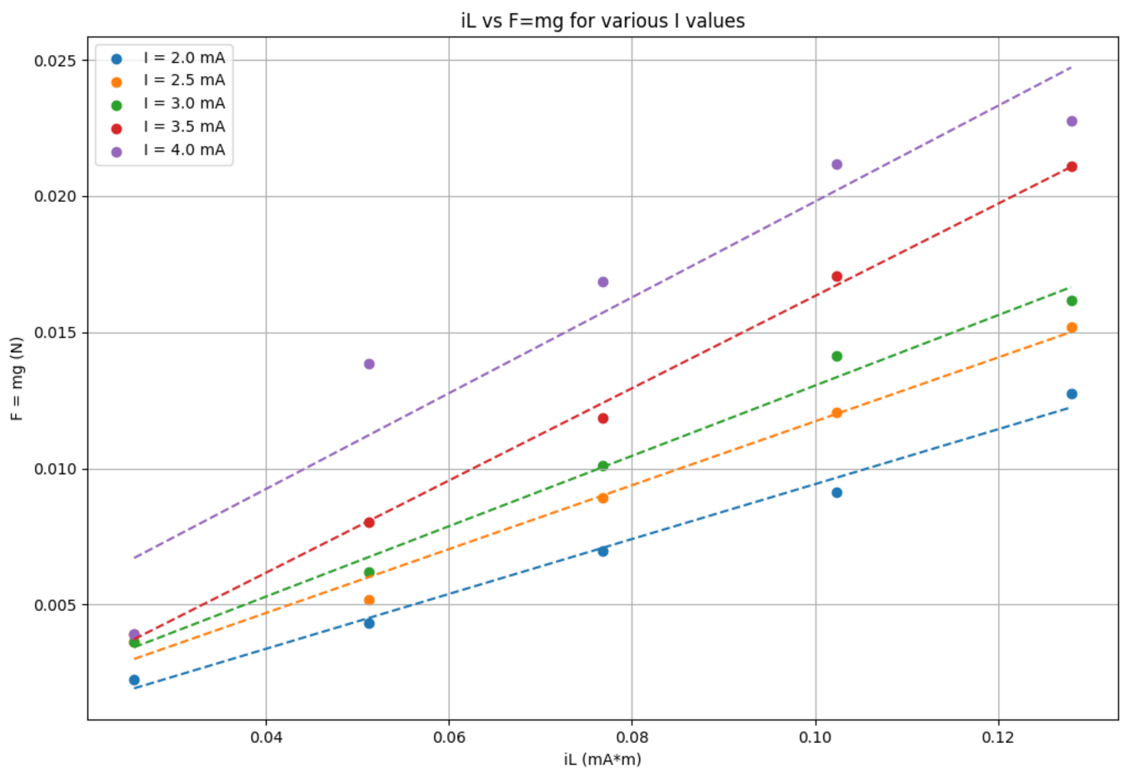

Figure 2: Graphical representation of the product of the rod's current and its length (iL) against the gravitational force acting on the rod $F = mg$. The slope of the linear fit represents the magnetic field strength B of the electromagnet.

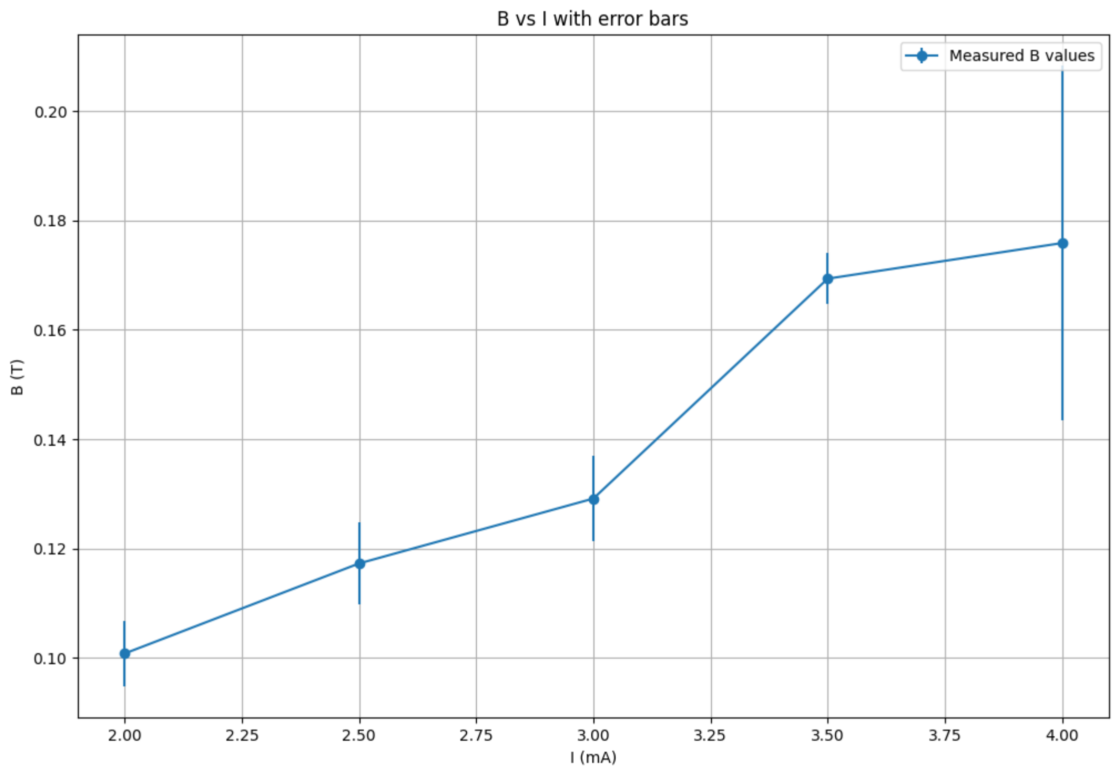

Figure 3: Relationship between the magnetic field strength B and the current I of the electromagnet.

Leveraging Faraday's Law of Electromagnetic Induction, it was observed that as the coil traversed through the magnetic field, distinct spikes in magnetic flux were evident. These fluctuations corresponded to the coil's entry and exit from the magnetic field. The phenomena observed align with Lenz's law, elucidating the nature and direction of the induced EMF based on the magnetic flux's rate of change.

Experimental factors, such as the precision of instruments, the quality of the electromagnet, or external electromagnetic interference, can influence the results and likely contributed to the observed error.

These experiments illustrated some of the principles governing magnetic fields and their interaction with conductors, offering a tangible understanding of foundational electromagnetic concepts.