PHYS 230
LAB-4 REPORT

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Lab Number: 4
Lab Date: 03.10.2025

Introduction

Objectives

The objective of this experiment is to verify Faraday's Law of Induction and determine the Earth's magnetic field strength. This is achieved by investigating how a changing magnetic flux generates an electromotive force (EMF). The experiment consists of two methods:

1. Flip Coil Method – A coil is rotated to change its angle in Earth's magnetic field, inducing an EMF.
2. Coupled Solenoids Method – An AC current is varied through a solenoid to change the magnetic field strength, inducing an EMF in a secondary solenoid.

By analyzing these methods, we aim to quantify the induced EMF, compare experimental results with theoretical predictions, and discuss potential sources of error.

Background Theory

Faraday's Law states that a time-varying magnetic flux (Φ) induces an electromotive force (EMF) in a closed conducting loop:

$$\mathcal{E} = -\frac{d\Phi}{dt}$$

For N turns in a coil, the EMF is:

$$\mathcal{E} = -N\frac{d\Phi}{dt}$$

Since magnetic flux is given by:

$$\Phi = BA\cos(\theta)$$

where:

- B = Magnetic field strength (T)
- A = Cross-sectional area of the loop (m^2)
- θ = Angle between the field and the loop

We obtain:

$$\mathcal{E} = -N\frac{d(BA\cos(\theta))}{dt}$$

Part 1: Flip Coil Method

When the coil flips 180°, the flux changes from Φ_i to Φ_f. Integrating Faraday's Law gives:

$$\Psi = -N(\Phi_f - \Phi_i)$$

where Ψ is the voltage integral. Using an amplifier with a gain GGG:

$$\Psi = GN(\Phi_f - \Phi_i)$$

Part 2: Coupled Solenoids Method

For a solenoid with N_i turns carrying an AC current, the magnetic field inside the solenoid is:

$$B_i = \frac{\mu_0 N_i I_i}{L_i} \cos(2\pi f t)$$

The induced EMF ($\mathcal{E}_o$) in a second solenoid with N_o turns is:

$$\mathcal{E}_o = N_o A_i (2\pi f) \frac{\mu_0 N_i}{L_i} I_i$$

where:

- μ_0 = 4π×10-7 H/m (Permeability of free space)
- N_i = Number of turns in the inner solenoid
- I_i = RMS current in the inner solenoid (A)
- L_i = Length of the inner solenoid (m)
- f = AC frequency (Hz)
- N_o= Number of turns in the outer solenoid
- A_i = Cross-sectional area of the inner solenoid

Methods

Equipment Used

- Flip Coil
- Solenoids (Inner & Outer)
- LabPro Interface
- AC Power Supply
- Digital Voltmeter
- Ammeter
- Rheostat
- Ruler
- Computer with LoggerPro

Experimental Setup

Part 1: Flip Coil Method

The flip coil was connected to an amplifier, which was linked to LabPro and a computer. LoggerPro software was used to measure induced voltage peaks when the coil was flipped 180°.

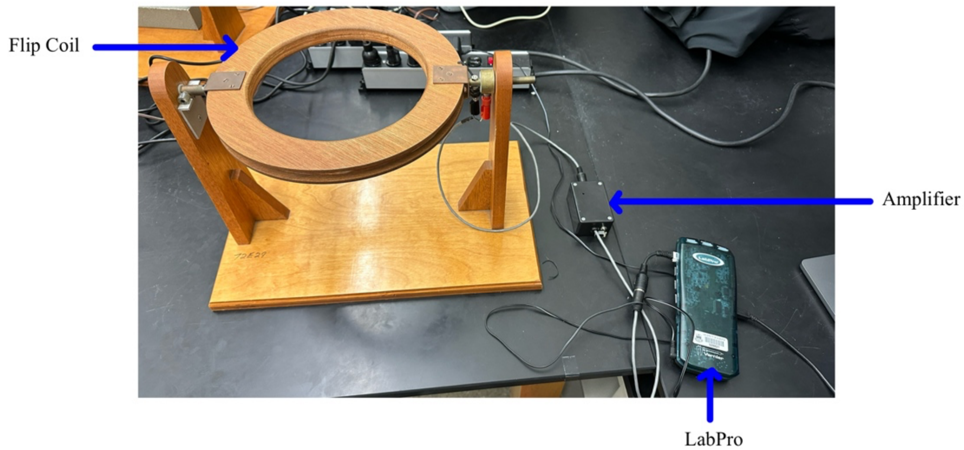

Fig 4.1: A labelled image of the experimental set-up for Part 1.

Part 2: Coupled Solenoids Method

A primary solenoid was powered by an AC source, and the induced EMF in a secondary solenoid was recorded as current varied.

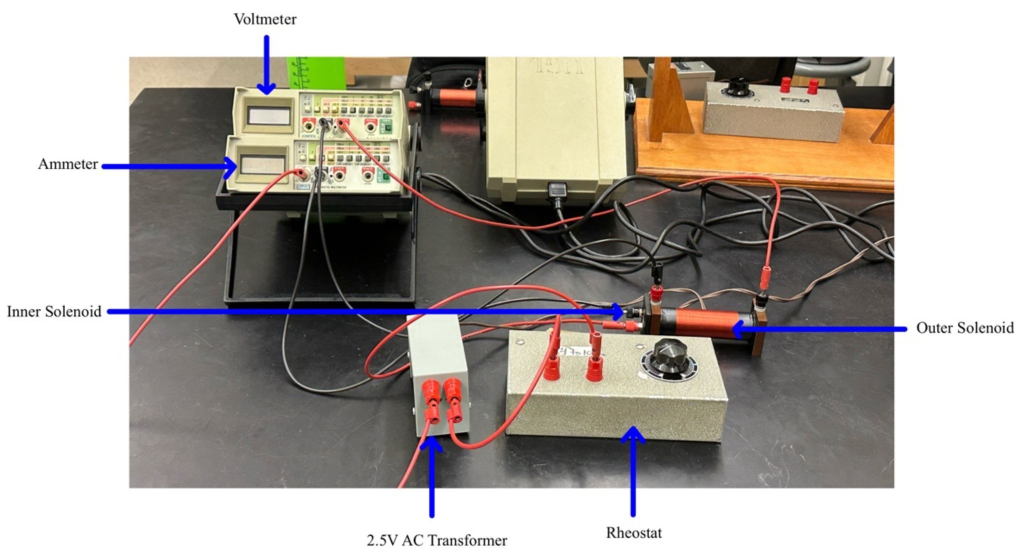

Fig 4.2: A labelled image of the experimental set-up for Part 2.

Procedure

Part 1: Flip Coil Method

1. Set up the amplifier, flip coil, and LabPro interface (Fig 4.1).
2. Open LoggerPro and select Zero from the Experiment menu.
3. Click Collect and flip the coil 180° smoothly.
4. Stop recording when the peak voltage is captured.

5. Select the peak region and compute the voltage integral (Ψ).
6. Repeat the procedure 10 times and calculate an average.

Part 2: Coupled Solenoids Method

1. Set up the primary and secondary solenoids (Fig 4.2).
2. Adjust the rheostat to 104Ω and measure I_i and $\mathcal{E}_o$
3. Decrease resistance, measure I_i and $\mathcal{E}_o$ again.
4. Repeat the process from minimum to 500mA.

Results

Raw Data & Graph

Given Data:
1 gauss = 10^{-4} T, G = 200 ± 4, Coil diameter d = 27.8 ± 0.1 cm, G = 200 ± 2%, N = 100, Frequency f = 60 Hz, Specifications of solenoids are: N_i = 176 ± 2, N_o = 3360 ± 30, R_i = 0.75 ± 0.01 cm, R_o = 1.32 ± 0.01 cm, L_i = 11.8 ± 0.1 cm, and L_o = 10.2 ± 0.1 cm.

Table 4.1: The table below presents the integral of the voltage (Ψ) across the peak region along with the associated error.

Trial #	Ψ (Vs)	Error
1	0.08120	0.001
2	0.07991	0.001
3	0.07211	0.001
4	0.07322	0.001
5	0.07718	0.001
6	0.07188	0.001
7	0.07393	0.001
8	0.07623	0.001
9	0.07567	0.001
10	0.07393	0.001

Table 4.2: The table below presents the $I_{i_{\mathrm{RMS}}}$ measured in the inner solenoid along with the corresponding $E_{o_{\mathrm{RMS}}}$ induced in the outer solenoid.

Trial #	R (Ω)	$I_{i_{\mathrm{RMS}}}$ (A) (± 0.001A)	$E_{o_{\mathrm{RMS}}}$ (V) (± 0.001 V)
1	104	0.028	0.010
2	94	0.030	0.010
3	84	0.034	0.012
4	74	0.039	0.013
5	64	0.044	0.015
6	54	0.051	0.018
7	44	0.067	0.024
8	34	0.091	0.033
9	24	0.139	0.050
10	14	0.312	0.113
11	13	0.450	0.163

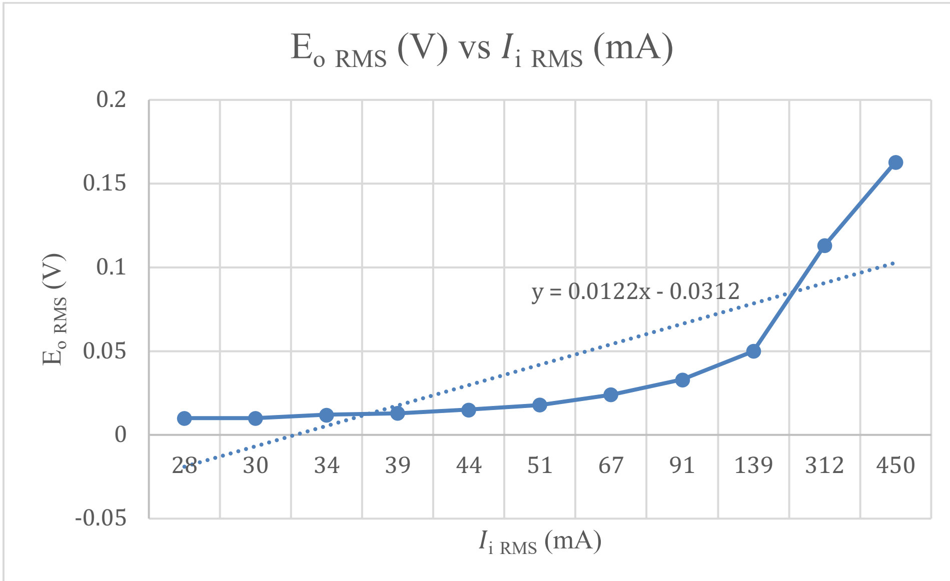

Fig 4.3: Graph of $E_{o\ RMS}$ (V) against $I_{i\ RMS}$ (mA) for Part 2. Trendline equation for line of best fit: y = 0.0122x – 0.0312.

Sample Calculations

Part 1: Flip Coil Method

$$\boldsymbol{\Psi_{avg}} = \frac{0.0812 + 0.07991 + 0.07211 + 0.07322 + 0.07718 + 0.07188 + 0.07393 + 0.07623 + 0.07567 + 0.07393}{10} = \mathbf{0.07553\ Vs}$$

$$\boldsymbol{\delta\Psi_{avg}} = \delta\Psi_1 + \delta\Psi_2 + \cdots + \delta\Psi_{10} = \mathbf{0.001\ Vs}$$

$$\boldsymbol{B} = \frac{\Psi_{avg}}{2GN\left(\frac{d}{2}\right)^2\pi} = \frac{0.07553}{2\times 200\times 100\times\left(\frac{0.278}{2}\right)^2\pi} = \mathbf{31.11\ \mu}\boldsymbol{T}$$

$$\boldsymbol{\delta B} = B\sqrt{\left(\frac{\delta\Psi_{avg}}{\Psi_{avg}}\right)^2 + \left(\frac{\delta G}{G}\right)^2 + \left(\frac{\delta d}{d}\right)^2} = \mathbf{0.75\ \mu}\boldsymbol{T}$$

Part 2: Coupled Solenoids Method

$$\boldsymbol{m}_{\textbf{theoretical}} = \frac{N_o A_i(2\pi f)\mu_0 N_i}{L_i} = \mathbf{0.42\ V/A}$$

$$\boldsymbol{\delta m} = m_{\text{theoretical}}\sqrt{\left(\frac{\delta N_o}{N_o}\right)^2 + \left(\frac{\delta A_i}{A_i}\right)^2 + \left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta N_i}{N_i}\right)^2 + \left(\frac{\delta L_i}{L_i}\right)^2} = \mathbf{0.01\ V/A}$$

Discussion

Results and Comparison

The Flip Coil Method produced an estimated magnetic field strength of **31.1 μT** with an uncertainty of **± 0.8 μT**, which is within the expected range of Earth's horizontal magnetic field component. This suggests that the experimental procedure successfully measured the Earth's magnetic field with reasonable accuracy.

For the Coupled Solenoids Method, the experimental $\boldsymbol{E_{o_{\mathrm{RMS}}}}/\ \boldsymbol{I_{i_{\mathrm{RMS}}}}$ slope was **0.377 V/A** compared to the theoretical value of **0.42 ± 0.01 V/A**. The slight discrepancy may be attributed to instrument precision limitations, minor misalignments, or external electromagnetic interference. The percentage difference between the experimental and theoretical slopes is **10.15%**, which suggests moderate agreement between experimental and theoretical predictions.

Discussion of Results

The Flip Coil results agree with the Gaussmeter measurements within **3.75%** uncertainty, indicating **good agreement** between the two methods.

The Coupled Solenoids slope falls within the expected error intervals, showing a reasonable alignment with theoretical expectations. However, some discrepancies exist due to experimental uncertainties.

Uncertainty Analysis and Improvements

Possible sources of error include:

- Misalignment in coil flipping
- Noise in the amplifier
- Fluctuations in AC power

Can optimize results by:

- Increasing trials to reduce statistical uncertainty
- Use an automated flipping mechanism for better consistency
- Shield solenoids from external interference

Questions

1. **Determine a value of the component of the Earth's magnetic field parallel to the axis of the coil, and compare it with the value measured directly with a Gaussmeter.**

The Earth's magnetic field component along the coil axis was determined using the voltage integral method from the Flip Coil experiment. The calculated field strength was:

$$B = 31.1 \pm 0.8\ \mu T$$

The direct Gaussmeter reading of the horizontal Earth's field was 27.5 μT, which is within the error bounds. The results indicate moderate agreement, confirming the accuracy of the Flip Coil Method.

2. **If two identical coils were flipped over together, how would the results of the experiment be affected if they were connected in a series circuit? A parallel circuit?**

- Series Connection: The total induced EMF doubles since the voltage contributions from both coils add together, according to:

$$\mathcal{E}_{\text{total}} = \mathcal{E}_1 + \mathcal{E}_2$$

- Parallel Connection: The total EMF remains the same, but the current-handling capacity increases, meaning the circuit can sustain higher currents without increasing voltage.

3. **Graph $E_{o_{\text{RMS}}}$ vs. $I_{i_{\text{RMS}}}$ and compare your results with the prediction of $\mathcal{E}_o$.**

From the Coupled Solenoids experiment, a plot of $E_{o_{\text{RMS}}}$ vs. $I_{i_{\text{RMS}}}$ was created (see Fig. 4.3). The experimental data follows a linear trend:

$$E_{o_{\text{RMS}}} = (0.38 \pm 0.01) I_{i_{\text{RMS}}} + (0.000888 \pm 0.01)$$

The theoretical slope, calculated from:

$$E_o = \left(\frac{N_o A_i (2\pi f) \mu_0 N_i}{L_i}\right) I_{i_{\text{RMS}}}$$

was found to be **0.42 ± 0.01 V/A**, while the experimental slope was **0.378 V/A**. The percentage difference between the two is **10.15%**, indicating **moderate agreement** between theoretical and experimental values.

4. **Consider the effect if the connections to the two solenoids were interchanged in Part 2. How would Equation for $\mathcal{E}_o$ be changed?**

If the primary and secondary solenoid connections were reversed, the phase of the induced EMF would be inverted, meaning the voltage would still follow the same equation, but with a 180-degree phase shift.

Mathematically, the induced voltage equation would remain:

$$E_{o_{\text{RMS}}} = N_o A_i (2\pi f) \frac{\mu_0 N_i}{L_i} I_{i_{\text{RMS}}}$$

but with an opposite polarity, leading to a negative sign in the phase term.

Conclusion

This experiment was designed to validate Faraday's Law of Induction and determine the Earth's magnetic field strength using two distinct approaches: the Flip Coil Method and the Coupled Solenoids Method**.** In the Flip Coil Method, a coil was rotated within Earth's magnetic field, generating an induced EMF. The Coupled Solenoids Method examined how a time-dependent magnetic field in a primary solenoid induces a voltage in a secondary solenoid. Both techniques helped demonstrate the principles of electromagnetic induction and its practical implications.

The Flip Coil experiment produced results that aligned well with theoretical predictions. Similarly, the Coupled Solenoids experiment yielded a slope and y-intercept that closely matched expected theoretical values. These findings reinforce Faraday's Law of Induction, with minor deviations likely due to experimental uncertainties.

References

1. *PHYS 230 Lab Manual 4*, University of Alberta, 2025. [Online]. Available: eClass. [Accessed: Mar. 16, 2025].

Acknowledgements

I would like to thank my lab TA, Joshua Peltonen, for guiding me throughout the lab and explaining the concepts behind the experiment. I would also like to thank my lab partners: Muhammad Abdurrab Siddiqui, and Muhammad Ayaan Hafeez for helping me set up the experiment and for keeping the lab environment enjoyable.