Chapter 8

Induction - Faraday's Law

Name:_____   **Lab Partner:**_____   **Section:**_____

8.1   Purpose

The purpose of this lab is to study induction. Faraday's law of induction and Lenz's law will
be explored.

8.2   Introduction

It is well known that a current flowing in a wire produces a magnetic field. Electric motors
use this fact to produce mechanical energy for many applications. A closely related effect is
induction. A **changing** magnetic field produces an electromotive force (EMF) or voltage
in a coil of wire. Alternating current (AC) electricity is produced at power plants using the
idea of induction.

A changing magnetic field in a loop of wire induces an electromotive force (EMF) or
voltage in the loop of wire. The effect was extensively investigated by Michael Faraday in
the first half of the 19th century.

Consider a coil of wire such as a solenoid. If a uniform magnetic field exists perpendicular
to the plane of the coils, i.e. along the axis of the solenoid, we define the **magnetic flux**,
Φ_B, as:

$$\Phi_B = B \cdot A \tag{8.1}$$

where A is the cross sectional area of the coil and B is the uniform magnetic field. If the
field is not constant nor perpendicular to the coil, the magnetic flux can be generalized as:

$$\Phi_B = \Sigma_{area}\vec{B} \cdot \Delta\vec{A} \quad (= \int \vec{B} \cdot d\vec{A}) \tag{8.2}$$

where $\Delta \vec{A}$ is a vector with magnitude equal to a small unit of area and the direction is perpendicular to the loop. Note this is a scalar since the magnetic flux is an 'inner' or 'dot' product. The unit of magnetic flux is the Weber which is a Tesla meter^2.

Faraday showed that an EMF is induced in a coil of wire when the magnetic flux changes in the loop. This EMF (voltage) causes an induced current to flow in the circuit. Faraday's law can be stated as:

- The magnitude of the induced EMF in a conducting loop is equal to the rate at which the magnetic flux, Φ_B, through the loop changes with time.

This can be expressed mathematically as:

$$EMF = -N\frac{\Delta \Phi_B}{\Delta t} \quad (= -N\frac{d\Phi_B}{dt}) \tag{8.3}$$

where N is the number of coils. Note that the EMF is largest when the **rate of change (derivative)** of the current is largest. (In alternating current circuits with inductance, the voltage is said to 'lag' behind the current by 90°.)

The negative sign in Faraday's law is known as **Lenz's law**. Lenz's law determines the direction of the induced EMF. Lenz's law can be stated as:

- An induced current has a direction such that the magnetic field due to the current opposes the change in the magnetic flux that induces the current.

Consider the situation where two coils are next to one another. If a current exists in one coil, a magnetic field is produced in both coils. If this current is changed, the magnetic field will change in both the current-carrying coil and the second coil. The changing flux in the second coil will result in an EMF due to Faraday's law. The details of the magnetic field and the flux depend on the geometry of the coils and the environment, e.g., how the coils are wound, the location of one coil with respect to the other, and the presence of magnetic material like iron near the coils. **If the geometry is fixed**, the magnetic field in the first coil is proportional to the current in the first coil. The flux through the second coil is then proportional to the current in the first coil. When the current is changed in the current carrying coil, the induced EMF in the second coil is proportional to the time rate of change in the current carrying coil:

$$EMF = -M\frac{\Delta I}{\Delta t} \quad (= -M\frac{dI}{dt}) \tag{8.4}$$

where $\frac{\Delta I}{\Delta t}$ is the rate of change of the current in the first coil and M is the mutual inductance of the coils. The unit of mutual inductance is the Henry (H), which is a Tesla · meter^2 per ampere.
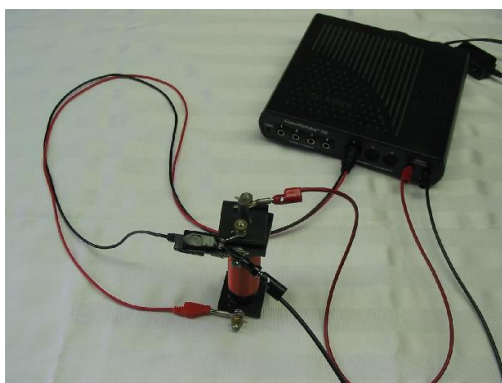
Figure 8.1: This photo shows the inner coil connected to the Science Workshop interface signal generator and the voltage probe connected to the outer coil. The current limiting resistor is connected between the inner coil and signal generator.

8.3 Procedure

The apparatus consists of two coils. The inner coil fits inside the outer coil. The iron rod fits inside of the inner coil. The outer coil is connected to the voltage probe to measure the induced voltage. In the second part of the experiment, the universal 550 interface 'signal generator' is used to provide an AC current in the inner coil (See Figure 8.1).

Special Cautions:

- Do not connect the inner coil to the signal generator output without the current limiting resistor.

8.3.1 Voltage Induced by a Permanent Magnet

- Remove the inner coil from the outer coil. The outer coil should remain attached to the voltage probe. Open the file 'Induction 1'. A plot of voltage vs time will appear.

- Begin data collection. Insert the permanent magnet into the coil. Move the magnet in and out. Vary the speed. Reverse the magnet. Move the coil with the magnet fixed.

- Answer the questions below. You should use the annotate feature of Capstone () to label the voltage plot. Save the data as a '.cap' file and send the appropriately labeled file to your TA.

    - How does the voltage depend on the speed of the magnet?

    - What is the voltage when the magnet is motionless?

    - What happened when the magnet was reversed?

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– Does it matter if the coil or the magnet moves?

8.3.2 Induced Voltage by a Time-Varying Current

- The outer coil should remain connected to the voltage probe. Place the inner coil completely inside the outer coil. The interface signal generator connections should be connected to the inner coil **through** the 20Ω current-limiting resistor. Refer to Figure 8.1. Verify the soft iron rod is inserted inside the inner (current carrying) coil.

- Open the file 'Induction 2'. A plot with two graphs (voltage vs. time and current vs. time) will appear. The voltage vs time is the induced outer coil voltage. The current vs time is the inner coil current. A plot of voltage vs. rate of current change ($\frac{dI}{dt}$ or $\frac{\Delta I}{\Delta t}$) will also be displayed. Click on the 'signal generator' to see the settings of the output current.

- Using the 'slope tool' on the current vs time graph, determine 5 points where the slope of the current is a maximum. Determine the voltage on the voltage vs time plot (using the 'smart tool') that corresponds to the points where the slope of the current vs time graph is a maximum. Record the values in Table 8.1

	Time (s)	Current Slope (A/s)	Induced Voltage (V)
1			
2			
3			
4			
5			

Table 8.1: Data table with maximum slope of the current

- Repeat the above step for points on the current vs time plot where the slope is ≈ zero i.e. constant current. Record the values in Table 8.2

	Time (s)	Current Slope (A/s)	Induced Voltage (V)
1			
2			
3			
4			
5			

Table 8.2: Data table with minimum slope of the current

- Make a linear fit to the voltage vs. current rate of change plot and record the slope of the curve.

Slope of V vs $\frac{dI}{dt}$ curve _____

What physical quantity does the slope of the curve represent?

- Save the data as a '.cap' file and send the appropriately labeled file to your TA.

- Repeat the procedure for the mutual inductance with the iron rod removed from the inner coil. Why are the results so different and what is the function of the iron rod?

8.3.3 Questions

1. In this lab the inner and outer coils are fixed and the current in the inner coil is changed. A generator uses a uniform magnetic field and rotates a coil in the magnetic field. How does the the EMF vary in time with such an arrangement?

2. If the negative sign (Lenz's law) was not in Faraday's law, what would be the result. Consider a coil with an increasing magnetic field perpendicular to the coil and describe the resulting EMF and induced current.

8.4 Conclusion

Write a detailed conclusion about what you have learned. Include all relevant numbers you have measured with errors. Sources of error should also be included.