

## Experiment 5: Faraday's Law

### OBJECTIVES

1. To become familiar with the concepts of changing magnetic flux and induced current associated with Faraday's Law of Induction.
2. To see how and why the direction of the magnetic force on a conductor carrying an induced current is consistent with Lenz's Law. Lenz's Law says that the system always responds so as to try to keep things the same.

### PRE-LAB READING

#### INTRODUCTION

In this lab you will develop an intuition for Faraday's and Lenz's Laws. By moving a coil of wire over a magnet you will change the magnetic flux through the coil, generating an EMF and hence current in the loop which you will measure using the 750.

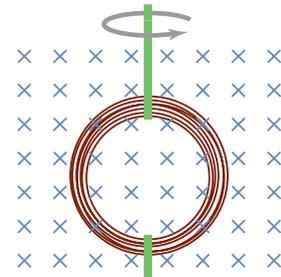
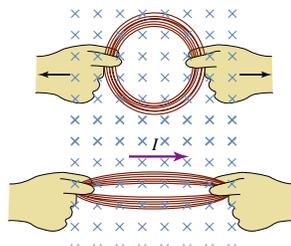
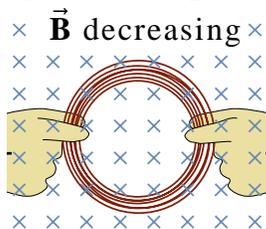
#### The Details: Faraday's Law

Faraday's Law states that a changing magnetic flux generates an EMF (electromotive force). Mathematically:

$$\mathcal{E} = -\frac{d\Phi_B}{dt}, \text{ where } \Phi_B = \iint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} \text{ is the magnetic flux, and } \mathcal{E} = \oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} \text{ is the EMF}$$

In the formula above,  $\vec{\mathbf{E}}$  is the electric field measured in the rest frame of the circuit, if the circuit is moving.

**Changing Magnetic Flux:** How do we get the magnetic flux  $\Phi_B$  to change? Looking at the integral in the case of a uniform magnetic field,  $\Phi_B = \iint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = BA \cos(\theta)$ , hints at three distinct methods: by changing the strength of the field, the area of the loop, or the angle of the loop. Pictures of these methods are shown below.



In each of the cases pictured above, the magnetic flux into the page is decreasing with time (because the (1) B field, (2) loop area or (3) projected area are decreasing with time). This decreasing flux creates an EMF. In which direction? We can use Lenz's Law to find out.

### Lenz's Law

Lenz's Law is a non-mathematical statement of Faraday's Law. It says that systems will always act to *oppose* changes in magnetic flux. For example, in each of the above cases the flux into the page is decreasing with time. The loop doesn't want a decreased flux, so it will generate a clockwise EMF, which will drive a clockwise current, creating a B field into the page (inside the loop) to make up for the lost flux. This, by the way, is the meaning of the minus sign in Faraday's law. I recommend that you use Lenz's Law to determine the direction of the EMF and then use Faraday's Law to calculate the amplitude. By the way, just as with Faraday's Law, you don't need a physical circuit to use Lenz's Law. Just pretend that there is a wire in which current could flow and ask in what direction it would need to flow to *oppose* the changing flux. In general, *opposing* a change in flux means *opposing* what is happening to change the flux (e.g. forces or torques *oppose* the change).

## APPARATUS

### 1. Magnet Stand

The magnetic flux of Faraday's Law will be generated by a high field permanent magnet, sitting on a support beam so that you may move a coil from above to below and back.

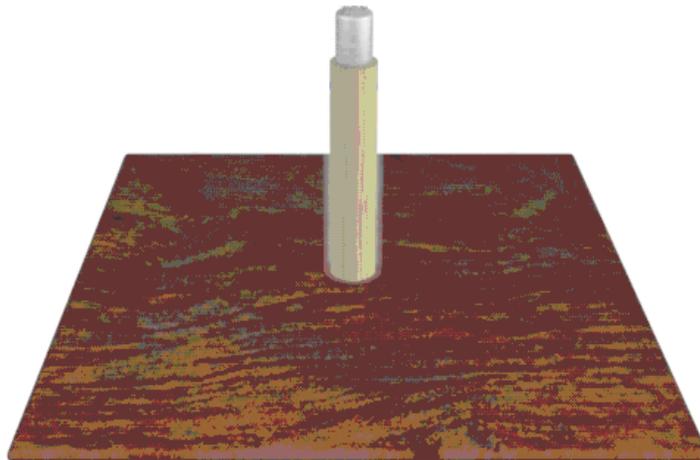


Figure 1 The Magnet Stand

## 2. Wire Loop, Current Sensor and Science Workshop 750 Interface

The magnetic field will penetrate a loop of wire, which you will plug into the current sensor, which is in turn plugged into channel A of the 750. In this lab we will use the convention that positive current flows counter-clockwise when observed from above. The current sensor records current that flows into its red terminal and out its negative terminal as positive, so make sure that you hook up the wire to the current sensor so that these two conventions are compatible with each other.



**Figure 2 The Current Sensor**

### GENERALIZED PROCEDURE

This lab consists of two parts. In each you will observe the effects (current & force) of moving a loop around a dipole.

#### **Part 1: Current and Flux through a Loop Moving Past a Dipole**

You will move a wire loop from above to below a magnetic dipole, and observe plots of the current flowing through the loop (measured) and the flux through the loop (calculated).

#### **Part 2: Feeling the Force**

In this part you will repeat the motion, using a hollow aluminum cylinder instead of the wire loop. In doing so you will be able to feel the force on the cylinder due to Lenz's Law.

**END OF PRE-LAB READING**

## Experiment 5: Faraday's Law

Answer these questions on a separate sheet of paper and turn them in before the lab

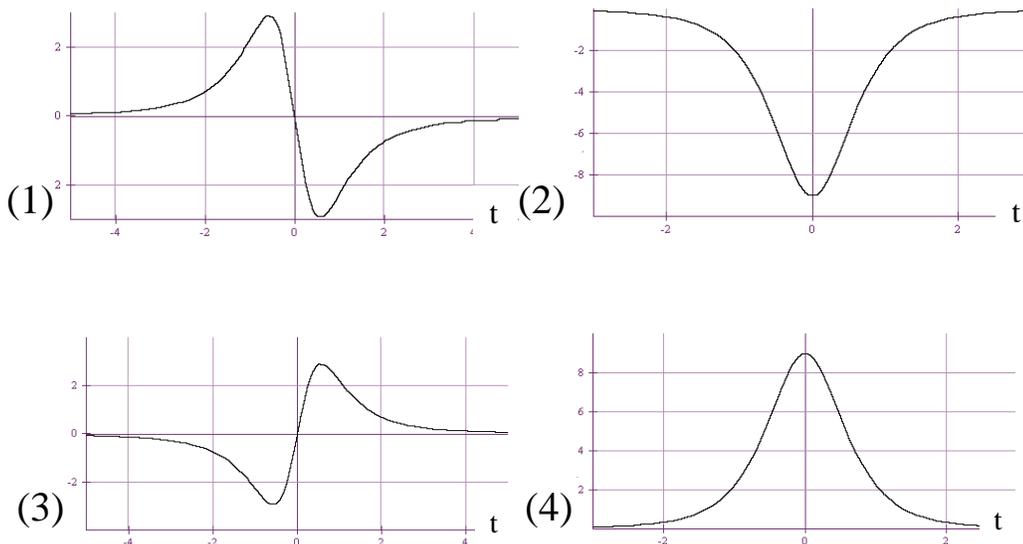
### 1. Calculating Flux from Current and Faraday's Law

In part 1 of this lab you will move a coil from well above to well below a strong permanent magnet. You will measure the current in the loop during this motion using a current sensor. The program will also display the flux “measured” through the loop, even though this value is never directly measured. In this problem you will understand how.

- (a) Starting from Faraday's Law and Ohm's law, write an equation relating the current in the loop to the time derivative of the flux through the loop.
- (b) Now integrate that expression to get the time dependence of the flux through the loop  $\Phi(t)$  as a function of current  $I(t)$ . What assumption must the software make (what value must it arbitrarily set) before it can plot flux vs. time?

### 2. Predictions: Coil Moving Past Magnetic Dipole

In moving the coil over the magnet, measurements of current and flux for each of several motions will look like one of the below plots. For current, counter-clockwise when viewed from above is positive. For flux, upwards is positive. The north pole of the magnet is pointing up.



Suppose you move the loop from well *above* the magnet to well *below* the magnet at a constant speed. Which graph most closely resembles the graph of:

- (a) *magnetic flux through the loop* as a function of time?  
(b) *current through the loop* as a function of time?

## 2. Predictions: Coil Moving Past Magnetic Dipole *continued*

Suppose you now move the loop from well *below* the magnet to well *above* the magnet at a constant speed. Which graph most closely resembles the graph of:

- (c) *magnetic flux through the loop* as a function of time?
- (d) *current through the loop* as a function of time?

## 3. Predictions: Force on Coil Moving Past Magnetic Dipole

In part 2 of this lab you will feel the force on a conducting loop as it moves past the magnet. For the following conditions, in what direction should the magnetic force point?

As you are moving the loop from well *above* the magnet to well *below* the magnet at a constant speed...

- (a) ... and the loop is *above* the magnet.
- (b) ... and the loop is *below* the magnet

As you are moving the loop from well *below* the magnet to well *above* the magnet at a constant speed...

- (c) ... and the loop is *below* the magnet.
- (d) ... and the loop is *above* the magnet

***Make sure that you record your answers to the previous two problems asking for predictions as you will need them in the lab.***

## 4. Feeling the Force

In part 2, rather than using the same coil we use in part 1, we will instead use an aluminum cylinder to “better feel” the force. What possible differences could make the cylinder work better than the coil? If we were to double the number of turns in the coil would we be more likely to be able to feel the force, less likely, or would there be no difference? In case you are interested, the wire is copper, and of roughly the same diameter as the thickness of the aluminum cylinder, although this information won’t necessarily help you in answering the question. (HINT: Write down the equation for force on a current in a magnetic field)

## IN-LAB ACTIVITIES

### EXPERIMENTAL SETUP

1. Download the LabView file and start up the program.
2. Connect the current sensor to channel A of the 750.
3. Connect the wire loop to the current sensor so that, starting at the black terminal, the wire loops counterclockwise (when viewed from above) and then enters the red terminal of the current sensor

### MEASUREMENTS

#### **Part 1: Current and Flux through a Loop Moving Past a Dipole**

1. Press 'Go' to start recording current and flux
2. Move the wire loop from well above to well below the magnet and back again. Try to make the motion as smooth as possible and at a constant velocity.

#### **Question 1:**

Did your measurements agree with your predictions? If not, which predictions did you miss and why?

#### **Part 2: Feeling the Force**

Although we could do this part of the lab with the same coil we just used, in order to better feel the force we will instead use an aluminum tube.

1. First hold the aluminum tube near the side of the magnet to convince yourself that Al is non-magnetic.
2. Place the tube over the Plexiglas and then push the tube downwards.
3. When you get to the bottom, pull the tube back up.

#### **Question 2:**

Did your measurements agree with your predictions? If not, which predictions did you miss and why?

### **Further Questions (for experiment, thought, future exam questions...)**

- What happens if you move the coil more quickly? Does the magnitude of the current change? Does the magnitude of the flux change? In part 2, does the force change?
- If the current, flux or force do not change in this situation, is there anything we could do to make them change? If they do change, what other changes could we make that would counter-act the change of moving more quickly?
- What happens to the force when the tube is exactly centered on the magnet? Why?
- Do the effects depend on history? In other words, is moving from the middle to the bottom any different if the motion started at the top than if it started at the bottom and reversed at the middle?
- What happens if we define the direction of positive current to be clockwise (in other words, if we flip the coil over)? Does this change have any affect on our definition of flux?