Experiment 11: Faraday's Law of Induction

Introduction

In 1831, Michael Faraday showed that a changing magnetic field can induce an emf in a circuit. Consider a conducting wire loop (a closed circuit) connected to an ammeter (A) with a bar magnet (initially at rest) placed above the center axis of the wire loop, as shown in Figure 1a. When the magnet is held stationary, there is no current in the loop, even if the magnet is inside the loop. However, when the magnet is brought near (or pulled away from) the loop, the ammeter needle deflects indicating an *induced* current in the loop produced by an induced emf (Figure 1b). From these observations, Faraday concluded that there exists a relationship between the induced current/emf and the changing magnetic field. The results of his experiments are now referred to as Faraday's Law of Induction. In general, Faraday's Law states that an induced emf ($\mathcal{E}$) along any closed path in a magnetic field is equal to the rate at which the magnetic flux changes along the surface of the area within the path. Quantitatively,

$$\mathcal{E} = -\frac{d\Phi_B}{dt} \tag{1}$$

where Φ_B is the magnetic flux through the closed path, expressed as $\Phi_B = \int \mathbf{B} \cdot d\mathbf{A}$.
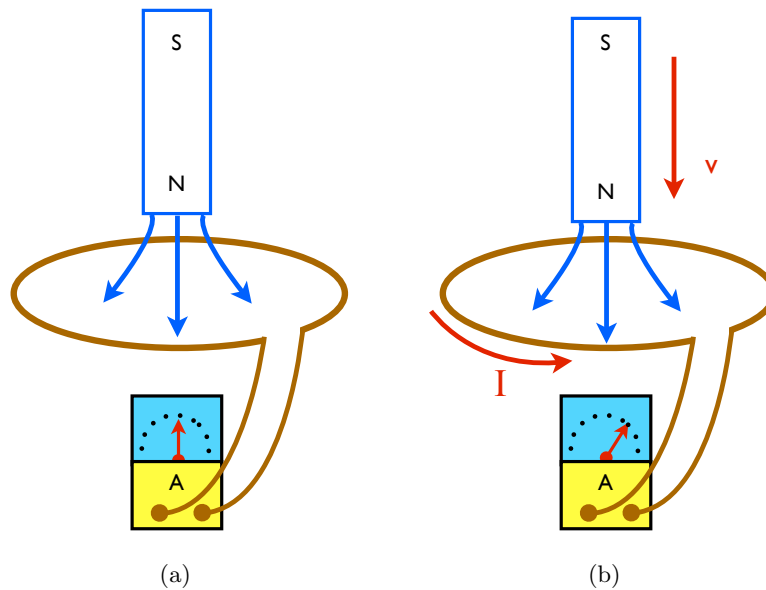

Figure 1: (a) When the bar magnet is held motionless near the loop, there is no induced current. (b) When the magnet is moved towards the loop, the ammeter is deflected, indicating an induced current I.

If the loop enclosing the area $\mathbf{A}$ lies in a uniform magnetic field $\mathbf{B}$, then the magnetic flux is equal to $BA\,cos(\theta)$, and thus the emf can be written as

$$\mathcal{E} = -\frac{d}{dt}(BA\,cos(\theta)) \tag{2}$$

The negative sign in Faraday's law indicates that the induced emf and the change in flux have opposite signs. This arises from a significant physical phenomena, referred to as Lenz' Law: the induced current is

always in a direction that opposes the change of flux that created it. That is, the induced current tends to keep the original magnetic flux from changing by creating a magnetic field in a direction that opposes the change in flux. As shown in Figure 1b, when the north end of the bar magnet is moved toward the loop, a current is induced. This induced current creates a magnetic field that counteracts the increasing flux of the bar magnet. Thus, the direction of induced current is such that its own (created) magnetic field is directed upwards. The direction of this field from the induced current can be determined by the *right hand rule for current loops*: if the fingers of the right hand curl around the loop in the direction of the current, the thumb then points in the direction of the magnetic field at the center of the loop.

Part 1- Observations of Faraday's Law and Lenz' Law

In this part of the lab we will explore the induced current in a conducting loop and verify its direction via Lenz' Law. You are given a conducting coil of N turns, a multimeter, and an unmarked magnet (that is the poles are not labeled). Your **first task** is to observe Faraday's/Lenz' Law in action. To observe these laws, simply connect the coil to the multimeter and examine what happens to the emf when the magnet is in motion through the coil. Answer and address the following questions with your observations:

1. When does the sign of the emf change? Does it only depend on the whether the North or South side of the magnet is brought near the coil? What happens to the emf if you bring one side of the magnet near the coil and then pass it through to the other side?

2. What happens if you bring the magnet toward the center of the coil and then suddenly bring it to rest?

3. Does the magnitude of the emf depend on the speed at which the magnet is traveling?

4. What orientation of the magnet gives you the largest emf?

5. Which end of the magnet is north? Verify this using the reference magnet (WARNING pinch hazard! do not bring the reference manget too close to your magnet).

Show that all of your observations above are consistent with Faraday's Law (Equations 1 and 2).

Part 2 - Faraday's Law with the Induction Wand

In this part of the lab we will use an Induction Wand to verify Faraday's Law of Induction and to measure the relationship between the magnitude of the induced electromotive force and the induced current with respect to the velocity of a coil traveling through a uniform magnetic field.

The induction wand consists of a copper wire coil with 200 turns and two terminals on the other end. The terminals will be connected to the computer interface via banana-jack cables allowing you to measure the induced emf/current. The wand will be set-up as a rigid pendulum, swinging through a uniform magnetic field provided by a variable gap magnet. The angle of release is measured with a rotary motion sensor that also acts as the pivot to the wand-pendulum set-up.

As the coil passes through the magnet, the changing magnetic flux will produce an emf given by

$$\mathcal{E} = -N\frac{d\Phi_B}{dt} \tag{3}$$

where N is the number of turns of wire in the coil. Since the magnetic field **B** produced by the parallel gap magnets is constant and perpendicular over the area **A**, we can write the induced emf as

$$\mathcal{E} = -NA\frac{\Delta B}{\Delta t} \tag{4}$$

where A is the area of the wire coil passing through the parallel gap magnets and N = 200.

Induction Wand Set-up Procedure:

1. Attach the induction wand to the rotary motion sensor. The motion sensor should already be clamped and connected to the computer interface.

2. Use the Hall Sensor Probe to measure the magnetic field between the plates. This is your constant value of **B**. Calculate the area A, given that the inner diameter of the wire coil is 1.9 cm and the outer diameter is 3.1 cm.

3. Align the gap between the magnet poles so the coil wand will be able to pass through without hitting the magnet plates. Adjust the height of the coil so that it will be in the middle of the magnetic field when it passes through. Make sure the wires of the sensors do not interfere with the motion.

4. Open the data acquisition software (Capstone) and select "Rotary Motion Sensor", "Current Sensor", and "Voltage Sensor" from the Hardware Tools options.

5. Find and display the Voltage vs Time graph and the Angular Velocity (rad/sec) vs Time graph. Positioning the two graphs on top of each other, on the top and bottom of the screen (clicking on Two Displays in template setup will do this), will give you a better sense of the induced emf versus position of the wand. The "record" and "stop" buttons at the bottom of the interface will start and stop the measurements.

6. Release the wand from an angle of 45°. You can check the angle using the rotary motion sensor. Observe the induced emf and the corresponding angular velocity as the wand passes through. You should see two emf peaks. Identify on the graph where the coil is entering the magnet and where it is leaving.

7. Use the magnifying/zoom tool to enlarge the peak portions of the emf graph. Highlight a single emf peak and find the average voltage. You can also use your cursor to determine the difference in time (Δt) from the beginning to the end of the first peak.

8. Repeat steps 6 and 7 for five different angles. Record the average emf for each case and its respective Δt.

Objectives and Analysis: While conducting the above procedure, prove and explain the following: (a) the induced emf is directly proportional to the velocity of the coil entering magnetic field, (b) the induced emf depends on the polarity of the magnet, and (c) that the sign of the emf corresponds to the direction expected using Lenz' Law. Remember to record all of your variables thoroughly and each of your measurements should be performed several times to minimize any errors. You may want to include any appropriate graphs that will help explain your results.

Answer the following questions in your lab report:

1. Why is the sign of the emf of the second peak opposite to the sign of the first peak?

2. Why is the emf zero when the coil is passing through the center of the magnetic plates?

3. Calculate the average emf using Equation 4. Compare your calculations to the emf value measured from the graphs.