

# ELECTROMAGNETIC INDUCTION

**OBJECTIVE:** To study the laws of electromagnetic induction (Faraday's law and Lenz's law).

**THEORY:** Electromagnetic induction is the process in which a magnetic field causes or *induces* an electric field. However, a "static" magnetic field will not do this; it takes a **changing** magnetic field. A changing  $B$ -field can be produced in several ways: (1) the current producing the  $B$ -field can change, (2) the source of the field (electromagnet or permanent magnet) can be in motion, or (3) the frame of reference in which the  $B$ -field is being observed can be in motion. The induced electric field exists only while the change is occurring. If there is no change, then there is no induction. When there are conductors present, the induced electric field is usually described in terms of an induced voltage, also called the 'electromotive force' (EMF). If the conductors form complete circuits, then the induced EMF's produce induced currents.

Faraday's law of induction relates the induced electric field to the changing magnetic field. For the case of a circuit, **Faraday's law** can be written as

$$EMF = \frac{\Delta\Phi}{\Delta t} ,$$

where  $\Phi$  is the magnetic flux through the circuit. When the  $B$ -field is uniform and at right angles to the area  $A$  bounded by the circuit, then the flux is simply  $B \cdot A$ . (For non-uniform fields, the flux must be calculated by integration.)

Often it is useful to distinguish between the case where the  $B$ -field passes through the area  $A$  in one direction (e.g., left to right) and the case where it passes through in the opposite direction (e.g., right to left). This can be done by letting the flux be positive in one case (it doesn't matter which) and negative in the other case. When this is done, a reversal of the field direction or a rotation of the circuit by  $180^\circ$  relative to the  $B$ -direction will cause a sign change in the flux through the circuit.

The minus sign in the Faraday's law equation gives information about the direction of the induced  $E$ -field and thus the sign (polarity) of the resulting induced EMF. When currents are possible, Lenz's law can be used to predict the current direction. A useful version of **Lenz's law** is:

***The induced current will appear in such a direction that the magnetic flux of the field caused by that current will tend to cancel the flux change that produced the current in the first place.***

In other words, the magnetic effects of the induced current opposes the change in conditions which produced it.

For this experiment, the secondary (yellow) coil and the meter comprise the circuit in which the induced EMF and induced current appear. The many turns in the coil magnify the small effects that would be observed with only a single turn.

**PROCEDURE:**

(In order to be sure that your observation of an effect was correct, you should repeat any step in this procedure as many times as you need to.)

**I. Bar magnet at rest inside the coil.**

1. Place the bar magnet inside the secondary coil (yellow coil) with the North pole inside.
  - a. Connect a microammeter across the terminals of the yellow coil.
  - b. Is there any measureable current with the magnet at rest in the yellow coil? \_\_\_\_\_
  - c. Was your observed result expected? Explain.

**II. Bar magnet moved.**

1. Move the magnet (with the **North** pole in the yellow coil) about half way **out** of the coil and then **remove** the rest quickly (with a jerk).
  - a. Was there a current as you removed the magnet? \_\_\_\_\_.
  - b. If so, which direction was the current? If the needle of the microammeter moves to the right (left), the current is entering the micrometer through the right (left) input.  
\_\_\_\_\_
  - c. If a current was produced, it created a magnetic field in the yellow coil. Determine which way the current was flowing through the yellow coil, and use the right hand rule to determine the direction of the resulting magnetic field induced in the yellow coil. Which end of the yellow coil was the North pole )?  
\_\_\_\_\_
  - d. Did this induced field in the yellow coil oppose or support the field of the bar magnet?  
\_\_\_\_\_
  - e. Comment on this observation in relation to Lenz's Law.
2. Does the speed at which you remove the magnet affect the **sign** (polarity) of the induced current? \_\_\_\_\_
3. Does the speed at which you remove the magnet affect the maximum **size** of the induced current? \_\_\_\_\_
4. Now **insert** the magnet (North pole in) about half way into the coil with a quick movement.
  - a. Which direction did the ammeter give for the current? \_\_\_\_\_
  - b. Which way did the induced magnetic field generated in the yellow coil by the induced current point (i.e., which end of the yellow coil was the North pole )? \_\_\_\_\_
  - c. Did this induced field oppose or support the field of the bar magnet? \_\_\_\_\_
  - d. Comment on this observation in relation to Lenz's Law.
5. Next with a quick movement **insert** the **South** pole of the magnet (as in step 4) and note the direction of the induced current.
  - a. Which way did the induced current go in the yellow coil? \_\_\_\_\_
6. Quickly **remove** the **South** pole of the magnet.
  - a) Which way did the induced current go in the yellow coil? \_\_\_\_\_
7. Are the observations of steps 5 and 6 consistent with your statement in step 4 and Lenz's Law? \_\_\_\_\_ Explain.

### III. Electromagnet moved.

The primary (blue) coil, which fits inside the secondary (yellow) coil, functions as an **electromagnet**. It produces a  $B$ -field with geometry similar to that of a permanent bar magnet, but the field magnitude is proportional to the current and the field direction reverses if the current direction is reversed.

1. From an inspection of the direction of the windings of the primary (blue, fewer turns, thicker) coil), determine which of its two terminals should be connected to the positive terminal of the power supply in order to make the bottom of the blue coil a North magnetic pole.
2. Connect the blue coil to a power supply with a switch in series so that the current to the coil can be turned on and off by closing and opening the switch. Leave the yellow coil connected to the microammeter.
3. Place the primary coil (blue) inside the secondary (yellow) coil. Close the switch and adjust the voltage control to the **lowest possible setting** that will give about 1 amp in the blue coil.
4. **Remove** the blue coil (electromagnet) from the yellow coil with a small jerk.
  - a. Which way did the induced current flow in the yellow coil? \_\_\_\_\_
  - b. Is this consistent with what happened when you removed a North pole of the permanent magnet from inside the yellow coil in Part II? \_\_\_\_\_
5. **Insert** the blue coil (electromagnet) into the yellow coil with a quick movement.
  - a. Which way did the induced current flow in the yellow coil? \_\_\_\_\_
  - b. Is this what you expected? \_\_\_\_\_

### IV. Current in the electromagnet switched off and on.

1. Set the current in the blue coil to about 1 amp as in Part III. Place the blue coil inside the yellow coil.
2. **Open** the switch. Which way did the induced current flow in the yellow coil? \_\_\_\_\_
3. **Close** the switch and again record which way did the induced current flow in the yellow coil \_\_\_\_\_
4. Explain why opening and closing the switch causes the direction of the induced current in the yellow coil to change.

### V. Effect of an iron core on the induced EMF.

1. Close the switch and set the power supply current at 0.5 amps using **the voltage control knob**.
2. Open and close the switch to the blue coil and note the size of the induced current in the yellow coil.

3. Now place the **iron** (heavier) rod about 1/3 inside the blue coil. Open and close the switch again.
  - a. Has the size of the induced current significantly increased? \_\_\_\_\_
  - b. Explain this observation.
  - c. Now move the iron rod about 2/3 the way inside the blue coil. Open and close the switch and note the size of the induced current.
  - d. What happens to the size of the induced current as more of the iron rod is included inside the blue coil? \_\_\_\_\_
  
4. Replace the pencil with the **magnesium** rod and repeat step 3. (The magnesium rod is much lighter in weight than the iron bar).
  - a. Do you still get a significant increase in the induced current over what you had originally with just air inside the coil? \_\_\_\_\_
  - b. Does the permanent magnet attract the **iron** bar? \_\_\_\_\_
  - c. Does the permanent magnet attract the **magnesium** bar? \_\_\_\_\_
  - d. Explain how all of these observations made in steps 3 and 4 relate using the principles of electromagnetic induction.

## VI. Effect of increasing current

1. Use the same circuit as in part V with the **iron** rod in completely inside the primary coil. See what the **level of current** in the electromagnet (primary coil) does to the induced current in the secondary coil as you open and close the switch to the electromagnet. Record your observations.
  - a. Does the induced current in the secondary coil depend on the amount of current in the electromagnet? \_\_\_\_\_
  
2. If a more detailed study were made, we would find that the induced current in the secondary coil depends linearly on the electromagnet current. Explain this linear dependence in terms of Faraday's Law and other relevant relationships.

## VII. Sending signals

1. Turn down the power supply for the blue coil and then disconnect the blue coil. Put the power supply off to one side, and put the blue coil and the bars inside the box. Replace the yellow coil with one of the big copper coils on the table (connect the big coil up in series with the DMM as an ammeter and with the other DMM in parallel as a voltmeter. Move the bar magnet into and out of the big coil as rapidly as you can. Look at the current and voltage induced across this coil and calculate the power output (recall  $P = I \cdot V$ ). Relate this power to the power required by one of the small light bulbs in the Ohm's Law experiment (about 1W).
  
2. Connect the sine wave generator to the **other** big coil and place this second (transmitting) coil next to the first (receiving) big coil. Turn up the voltage on the sine wave generator. Is there a current and voltage induced across the receiving coil due to the current in the transmitting coil from the sine wave generator? (You may have to change the scale on the voltage DMM. If you see a 1 displayed, that means that you must increase the range by pressing the next range button on the DMM.) Does this induced current in the receiving coil depend on the distance between the two coils? Does this induced current depend on the frequency at which the sine wave generator is set? Can an iron bar placed between the two coils affect the current in the receiving coil?