EXPERIMENT 13
QUALITATIVE STUDY OF INDUCED EMF

I. THEORY

Along the extended central axis of a bar magnet, the magnetic field vector $\vec{B}$, on the side nearer the North pole, points away from this pole. On the side nearer the South pole the vector $\vec{B}$ points toward the pole.

In both of these cases, the magnitude of the magnetic field decreases with increasing distance from the magnet.

When current exists in a coil it creates a magnetic field both inside and outside the coil. The magnitude of the field is directly proportional to the current, and is greater inside the coil than outside. The central axis of the coil is a line through the center of the coil and perpendicular to the planes containing the turns of wire. Along the central axis, the field is parallel to the axis itself.

The direction of the field along the central axis of the coil is related to the sense of the current by one of several right hand rules that are useful in electromagnetic theory. This rule states that if you curl the fingers of your right hand around the coil in such a way that your fingers point in the same sense as the conventional current, then your extended thumb points in the direction of the magnetic field vector. This rule is a special case of the more general rule which states that if you point your extended right thumb in the direction of the conventional current in a wire, then your curled fingers point in the direction of the magnetic field surrounding the wire.

If a ferromagnetic material such as iron or steel is inserted into the coil, the magnetic field is greatly strengthened because the material becomes magnetized like a bar magnet and adds its field onto the field due to the current alone. In this case the strength of the resultant field is no longer directly proportional to the current, though the field does increase as the current increases, up to the point of magnetic saturation, where any additional field strength is due only to the current itself.

If a coil is placed in a **uniform** magnetic field, the magnetic flux through one turn of the coil is defined by the equation

$$\Phi_B = BA \cos\theta$$

in which B is the field strength, A is the area of the turn and θ is the angle between the field vector and the central axis of the coil. If the field is parallel to the central axis of the coil, that is, perpendicular to the plane of the turn, the flux is given simply by BA. If the field varies in either magnitude or direction, calculus is required to determine the flux.

Faraday's Law states that when the magnetic flux through a coil of N turns changes, the induced emf is given by

$$\varepsilon = -N \, \Delta\Phi_B/\Delta t$$

The emf is therefore proportional to the number of turns and also to the rate of change of the flux through one turn. This assumes that the flux is the same through all turns at any instant, and if this is not true an average value is often used to represent all turns.

If the coil is part of a complete circuit, as when the two leads are connected together or when they are connected to an electrical meter, as in this experiment, then an induced current exists as well as an induced emf. The magnitude of the current at any instant is the ratio of the emf to the total resistance in the circuit.

If an iron rod is threaded through the hole at the center of a coil which is connected to a power supply, the current in the coil will create a magnetic field which will magnetize the rod. If the rod is threaded through the hole in a second coil which is connected to an electrical meter, currents can be induced in the second coil by varying the current in the first coil, which varies the degree of magnetization of the rod.

The reason for the negative sign in Faraday's Law is best expressed by Lenz's Law, which states that an induced current opposes whatever change caused the induced current. For example, if the flux through a coil increases for any reason, creating an induced current in the coil, then the additional magnetic field, created by the induced current, must be in the opposite direction from the original field, thus opposing the increase of the flux. On the other hand, if the flux decreases for any reason, then the field created by the induced current must be in the same direction as the original field, thus opposing the decrease of the flux.

The purposes of this experiment are to test Faraday's Law qualitatively and to test Lenz's Law.

A galvanometer will be used to test the sense of each current. In order to determine whether a deflection of the galvanometer needle to the right, for example, means that conventional current is entering the left binding post of the galvanometer or the right post, we will connect a power supply to the galvanometer and observe the direction of the deflection. Because the polarity of the power supply is known, there is no question as to which binding post of the galvanometer the conventional current enters.

The galvanometer has three levels of sensitivity, selected by pushing one of three buttons. The left button is least sensitive, the middle button more sensitive, and the right button most sensitive. If in doubt as to which button to use, always start with the *least sensitive* button so as to avoid the possibility of damaging the meter.

The galvanometer can be used to determine relative magnitudes of induced currents but, of course, the same level of sensitivity must be used for all cases compared.

II. LABORATORY PROCEDURE

1. Check to see that all three buttons of the galvanometer are up. If any appears to be in the depressed position, rotate it to release it.

2. Test the galvanometer as follows: Connect the positive (red) terminal of the power supply to the left terminal of the galvanometer. (Left is defined as you look at the face of the meter.) Connect the negative (black) terminal of the power supply to the right binding post. Rotate the VOLTAGE and CURRENT knobs counter-clockwise to their full extent. Plug in and turn on the power supply. Rotate the CURRENT control knob about one half revolution. Hold down the left button of the galvanometer and slowly turn up the power supply voltage, until a deflection of the meter is observed. Record the direction of the deflection. In the remainder of the experiment, you will know that whenever the needle deflects in this direction conventional current is entering the left binding post of the galvanometer. Turn the VOLTAGE and CURRENT control knobs of the power supply to zero, and turn the power supply off. Disconnect the galvanometer from the power supply.

3. Test the polarity of the bar magnet as follows: Place a compass on a level surface well away from any iron or steel, any electrical currents and any other magnets (such as other compasses). The bottom of your inverted lab box should work. Determine the North pole of the compass by observing its orientation in the Earth's magnetic field. Then, find by trial and error which pole of the bar magnet repels the North pole of the compass and attracts the South pole. This pole of the bar magnet is the North pole, and should be labeled "N".

4. Examine one of the coils. The side with the binding posts will be called the front of the coil. When the coil is oriented with the front upward and the binding posts on the side of the coil nearest you, then the post on the left will be called post A, the other one post B. On your data sheet make a simple diagram of the front of the coil, with the posts labeled.

5. By inspection, verify that if a conventional current enters the coil at post A and continues through the coil to post B, then the imaginary positive charges in motion, which constitute the current, will move in a clockwise sense, as the coil is viewed from the front. Verify this for the second coil as well. By the right hand rule mentioned earlier, the magnetic field created by the current along the axis of the coils will be directed from the front of the coil toward the back.

6. Connect post A of the coil to the left binding post of the galvanometer; connect post B of the coil to the right post of the galvanometer. Rest the coil on the table with its front upward.

7. Insert the North pole of the bar magnet into the center of the coil. Hold the middle button of the galvanometer down. Lift the magnet slowly and record the magnitude (in arbitrary units, as given on the scale of the meter) and direction of the deflection. If the deflection exceeded 20 units on the scale, do it again, more slowly this time and record the reduced value. If the deflection is too small to read, repeat using the right button of the galvanometer and record the new value.

8. Repeat step 7 using the same button used to record the value of the deflection, moving the magnet more rapidly this time and record only the magnitude of the deflection.

9. Repeat step 8, this time inserting the South pole of the magnet into the center of the coil, and pulling it out. Record only the direction of the deflection.

10. Hold down the same button on the galvanometer used in the previous steps. With the North pole of the magnet pointed toward the front of the coil, but some distance away along the central axis, move the magnet rapidly toward the coil and record only the direction of the deflection. DO NOT STRIKE THE MAGNET AGAINST THE COIL OR TABLE.

11. Insert the North pole of the magnet into the center of the coil. Lift the coil and magnet some distance above the table. Hold down the same button on the galvanometer used in the previous steps. Hold the magnet still and move the coil slowly away from the magnet. Record only the direction of the deflection.

12. Check to see that the power supply is turned off and that the VOLTAGE and CURRENT control knobs are is set for zero output. With the coil (now called Coil #1) still connected to the galvanometer as before, connect post A of a second coil (Coil #2) to the positive binding post of the power supply, and connect post B through a telegraph key to the negative binding post. Do not connect Coil #1 or the galvanometer to Coil #2 or to the power supply.

13. With the front of each coil upward, hold Coil #1 directly above Coil #2 and as close to it as possible, but with the central axes of both coils vertical. Turn on the power supply, rotate the CURRENT control knob to its full clockwise position and rotate the VOLTAGE control knob until the voltage display reads 8.0 V. Hold the right button of the galvanometer down and close the telegraph key. Record only the magnitude of the deflection.

14. Repeat step 13, this time holding Coil #1 so that its central axis is horizontal, while the central axis of Coil #2 remains vertical. Record only the magnitude of the deflection.

15. With both coils connected as in step 13, thread the iron rod (not the bar magnet) through the holes in both coils with the binding posts of both coils facing in the same direction along the rod. Set the power supply for 1.0 V. Hold the middle button of the galvanometer down.

   a. Close the telegraph key and hold it down. Record the magnitude and direction of the deflection.

   b. Record the direction of the deflection as you release the telegraph key.

16. Set the power supply for 2.0 V and repeat step 15a.

III. CALCULATIONS

1. Compare the results of II-7 and 8. How does Faraday's Law explain qualitatively the difference in deflections?

2. For procedure II-7:

   a. Draw a diagram of Coil #1 and the galvanometer, including labeled binding posts of each. Show the electrical connections between the two.

   b. Draw a diagram of the side view of the coil with the front side labeled. Include the moving bar magnet with polarity and velocity vector, v, indicated.

   c. In the diagram of part b, add a vector B which shows the direction (at the center of the coil) of the magnetic field due only to the presence of the bar magnet. This vector points away from the North pole of the magnet. Remembering that the strength of the magnetic field of the bar magnet decreases with increasing distance from the magnet, does the magnitude of this field increase or decrease due to the motion of the magnet?

   d. By Lenz's Law should the magnetic field due only to the current induced in the coil be in the same direction as the field due only to the magnet, or in the opposite direction?

   e. Using the right hand rule, should the induced current go from binding post A to binding post B within the coil itself, or from B to A?

   f. Should the induced current enter the left or right binding post of the galvanometer?

   g. Should the galvanometer deflect to the left or to the right?

   h. Does the theoretical conclusion of part g agree with the observation of II-7? If not, review all of the previous analysis.

3. For procedure II-9:

   a. Draw a diagram of Coil #1 and the galvanometer, including labeled binding posts of each. Show the electrical connections between the two.

   b. Draw a diagram of the side view of the coil with the front side labeled. Include the moving bar magnet with polarity and velocity vector, v, indicated.

   c. In the diagram of part b, add a vector B which shows the direction (at the center of the coil) of the magnetic field due only to the presence of the bar magnet. This vector points toward the South pole of the magnet. Does the magnitude of this field increase or decrease due to the motion of the magnet?

   d. By Lenz's Law should the magnetic field due only to the current induced in the coil be in the same direction as the field due only to the magnet, or in the opposite direction?

   e. Using the right hand rule, should the induced current go from binding post A to binding post B within the coil itself, or from B to A?

    f. Should the induced current enter the left or right binding post of the galvanometer?

    g. Should the galvanometer deflect to the left or to the right?

    h. Does the theoretical conclusion of part g agree with the observation of II-9? If not, review all of the previous analysis.

4. For procedure II-10:

    a. Draw a diagram of Coil #1 and the galvanometer, including labeled binding posts of each. Show the electrical connections between the two.

    b. Draw a diagram of the side view of the coil with the front side labeled. Include the moving bar magnet with polarity and velocity vector, v, indicated.

    c. In the diagram of part b, add a vector B which shows the direction (at the center of the coil) of the magnetic field due only to the presence of the bar magnet. Does the magnitude of this field increase or decrease due to the motion of the magnet?

    d. By Lenz's Law should the magnetic field due only to the current induced in the coil be in the same direction as the field due only to the magnet, or in the opposite direction?

    e. Using the right hand rule, should the induced current go from binding post A to binding post B within the coil itself, or from B to A?

    f. Should the induced current enter the left or right binding post of the galvanometer?

    g. Should the galvanometer deflect to the left or to the right?

    h. Does the theoretical conclusion of part g agree with the observation of II-10? If not, review all of the previous analysis.

5. Comparing the procedures in II-7 and II-11, is absolute motion or relative motion more important in generating an emf with a magnet and a coil?

6. Which equation in section I of this experiment explains the difference between the results of the procedures of II-13 and II-14? Explain briefly.

7. For procedure II-15a:

    a. Draw diagrams of the two circuits, showing front views of the two coils, with labeled binding posts showing all electrical connections. Include the polarity of the power supply. Do not include the iron rod in this diagram.

    b. Draw a diagram showing side views of the two coils, as placed on the iron rod. Show the binding posts of the two coils pointing in the same direction.

    c. According to the diagram in part a, did the conventional current in Coil #2 (connected to the power supply) flow from post A to post B within the coil or from B to A?

    d. Show in the diagram in part b the direction of the magnetic field vector in the rod due only to the current in Coil #2.

e. Did the magnetic field vector of part d increase or decrease in magnitude immediately after the telegraph key was closed?

f. Using Lenz's Law what must be the direction in the diagram of part b of the magnetic field due only to the current induced in Coil #1?

g. Using the previous result, should the current induced in Coil #1 go from post A to post B within the coil or from B to A?

h. Should the current induced in Coil #1 enter the left or right binding post of the galvanometer?

i. Should the galvanometer needle have deflected to the left or to the right?

j. Does the conclusion of part i agree with the observation in procedure II-15a? If not, review all of the preceding analysis.

8. Explain briefly why the deflection of the galvanometer in procedure II-15b was in the opposite direction from the deflection in procedure II-15a.

9. Explain briefly why the magnitude of the deflection in procedure II-16 differed from that in procedure II-15a.