

Electromagnetic Induction - A

APPARATUS

1. Two 225-turn coils
2. Table Galvanometer
3. Rheostat
4. Iron and aluminum rods
5. Large circular loop mounted on board
6. AC ammeter
7. Variac
8. Search coil
9. Oscilloscope Tektronix TDS1002 (see "Introduction to the Oscilloscope" on page 12)

INTRODUCTION

In this experiment we will produce an electric current by electromagnetic induction. We will demonstrate Faraday's law of induction and also Lenz's Law (conservation of energy). Qualitatively, we will show how the magnetic field \vec{B} and magnetic flux Φ can be measured with the aid of a search coil.

According to Faraday's law, if the magnetic flux through a loop of wire is changing, there is an electric field induced. Consequently, an electric current flows in the loop. The magnetic flux Φ is given by $\Phi = B_{\perp}A$, where B_{\perp} is the magnetic field perpendicular to the plane of the loop and A is the area of the loop. The product of the electric field E by the length of the loop ($2\pi rE$) is the induced voltage V_i (obsolete term: electromotive force). Faraday's law states that:

$$\begin{aligned}V_i &= \text{const.} \times \frac{d\Phi}{dt} \\ &= \text{const.} \times \frac{d}{dt}(B_{\perp}A)\end{aligned}$$

In Part I we shall verify some aspects of this law by observing the current induced in a coil of wire as a permanent magnet is moved (or held steady) near the coil.

In Part II the current in the coil of wire will again be observed, but the field at the coil will be caused by a current in another coil of wire held nearby. The variation in field can be caused either by moving the coils relative to one another or by varying the current in the coil which is setting up the field (see Fig. 2), in this part a study will also be made of the direction of the induced current (Lenz's Law).

In Part III the induced voltage will be observed with the aid of an oscilloscope.

Part I: Observation of induction using permanent magnet and coil

Connect a coil of wire to a sensitive galvanometer as shown in Fig. 1. If one pole of a bar magnet

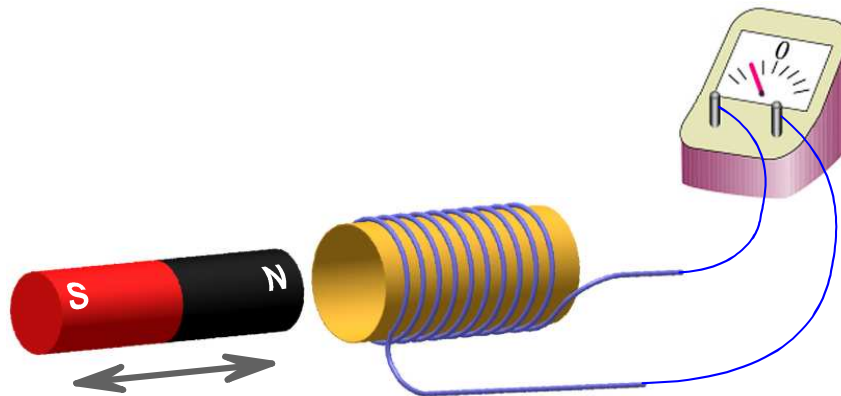


Figure 1: Electromagnetic induction with permanent magnet and coil.

is thrust into the coil, the galvanometer will deflect, indicating a momentary current in the coil. As long as the bar magnet remains at rest within the coil, no current is induced, if, however, the magnet is suddenly removed from the coil the galvanometer will indicate a current in the direction opposite to that at first observed.

The faster the motion of the magnet, the larger the induced current, as shown by larger deflection of the galvanometer. The discovery of this means of producing an electric current with a moving magnet led to the development of the electric generator.

Part II Lenz's Law

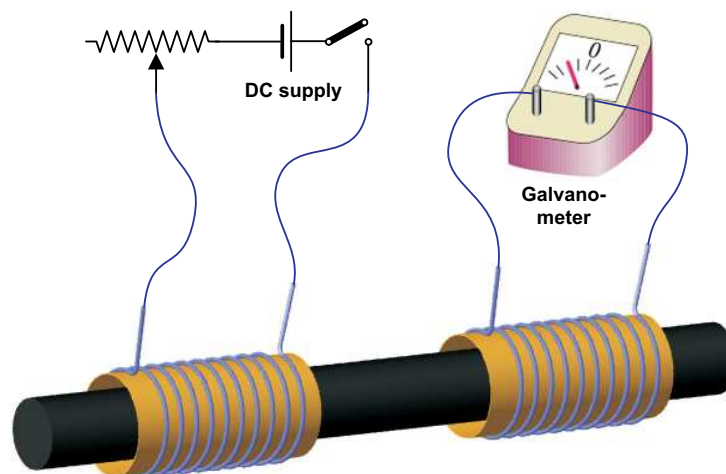


Figure 2: Electromagnetic induction with two coils.

Slide the two 225-turn coils on the iron rod so that their windings have the same sense of rotation

around the coils. Connect one coil in series with the DC supply, the switch, and the small rheostat (see Fig. 2). From the battery polarity note the direction of current in the coil when the switch is closed. Connect the two terminals of the second coil directly to the table galvanometer. Note that for this galvanometer the needle deflects toward the terminal at which current is entering. Deduce the current direction in the second coil when the switch to the first coil is closed. Secondly, leave the switch closed for a while and then deduce the current direction in the second coil when the switch is opened.

Make a sketch similar to Fig. 2, showing the direction of the current in the second coil for the two cases and interpret by Lenz's Law.

As a demonstration of the effect of iron, repeat an observation of the galvanometer throw with the iron removed, but the coils in the same relative position to each other.

Part III: Observation of induction within a coil

In this part of the experiment we will demonstrate how the magnetic flux, and therefore the magnetic field \vec{B} , can be measured using a search-coil and an oscilloscope. If we have a coil of wire

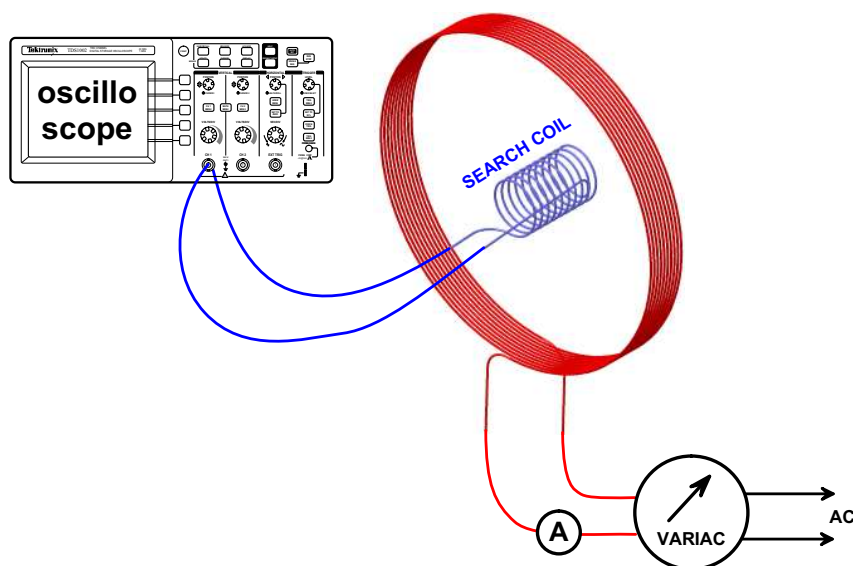


Figure 3: Electromagnetic induction within a coil.

connected in series with a galvanometer (Fig. 1), the galvanometer will show a deflection which is proportional to the rate of change of magnetic flux through the open area A of the loop. Such a loop is called a search coil. Thus, if we produce a varying magnetic field, and thus a varying flux, we can detect it using a search coil connected to a galvanometer.

A varying magnetic field is produced by a separate circuit, shown in Fig. 3, in which the current varies. We could therefore produce a varying magnetic field by using an alternating current (AC). The difficulty with this method, however, is that it produces a magnetic field which changes di-

rection, and the galvanometer needle would have to change direction to either side of zero. For a 60-cycle signal, the galvanometer needle has to change direction 120 times each second. The galvanometer needle cannot respond that quickly and would therefore read an average zero signal. In order to avoid this difficulty, we replace the galvanometer by an oscilloscope which can record quickly changing signals.

If we connect the terminals of the search coil to the CH1 input of the oscilloscope, we will observe the trace as a sine curve. At any point on the time axis, the distance of the trace from the time axis is proportional to the induced voltage across the terminals of the search coil.

According to Fig. 3, a variac (autotransformer) is connected to the AC line and the output of the variac is used to feed the circuit which consists of a large coil in series with an ammeter.

Before turning on the power, check to see that the dial on the variac is set for a minimum value. After the power is on, slowly increase the setting until the AC ammeter reads 1 A. Note that the reading on the ammeter is affected by its proximity and orientation with respect to the large coil. Attempt to position the meter so that this effect is a minimum.

It can be shown that the amplitude of the flux through the search coil is proportional to the induced voltage V_i :

$$\Phi = k V_i$$

- (a) Place the search coil in its holder at the center of the large coil. Adjust the current through the large coil to read 1 A. The search coil and the large coil must be parallel.

Keeping the search coil parallel to the plane of the large loop, measure the amplitude of the sine curve along the axis of the large loop at 0, 10, 20 and 30 cm from the center of the large coil and plot the amplitude vs. distance.

Note: Holes on the plate for placement of the search coil are spaced 5 cm apart.

- (b) Place the search coil at the center of the large coil. Measure the flux (the amplitude of the sine curve) when the normal to the search coil makes angles 0° , 15° , 30° , 45° , 60° , 75° and 90° with the normal to the large coil.

Plot the flux (amplitude of the sine curve) vs. angle, and on the same graph show a plot of the amplitude of the sine curve at 0° multiplied by the cosine of the angle between normals of the two coils. Compare these two curves.

Question: How does the flux depend on the angle?

Electromagnetic Induction - B

APPARATUS

1. DC Supply line
2. Bar magnet, polarity unmarked
3. U shaped piece of iron
4. Two 225-turn short air core solenoids
5. Cenco galvanometer
6. 400-turn large induction coil
7. 1000-turn search (pick-up) coil
8. AC ammeter
9. Variac
10. Oscilloscope Tektronix TDS1002 (see "Introduction to the Oscilloscope" on page 12)
11. Switch
12. 8" x 10" linear graph paper (supplied by instructor)

INTRODUCTION

This experiment is divided into two parts; the first is devoted to exhibiting the phenomenon of electromagnetic induction in a qualitative manner. It includes a test of the student's ability to use Lenz's Law. The second part tests one's ability to measure the induced voltage V , generated in a search coil by a changing magnetic flux. The student will be expected to know and understand the expressions $B = \mu_0 n I$ and $B = \frac{\mu_0 N I}{2R}$ which refer to the fields inside a long air core solenoid and at the center of a circular loop carrying current, respectively.

Part A: Electromagnetic Induction and Lenz's Law

PROCEDURE

(1) Connect the terminals of one of the 225-turn coils directly to the galvanometer and observe what happens to the galvanometer needle as one end of the bar magnet is moved in and out of the coil. Record the letter which appears on one end of the magnet and determine by means of Lenz's Law whether this end corresponds to the north or south magnetic pole. In order to do this you must know

- (a) the direction in which the turns have been placed on your coil
- (b) that the fieldlines are continuous and that their direction external to the magnet is out from the north magnetic pole and into the south pole piece,
- (c) that the galvanometer needle deflects to the right when the current enters through the right terminal and leaves through the left; the needle deflects to the left when the current direction is reversed.

(2) Leaving the galvanometer connected to the 225-turn coil, place it near the second 225-turn coil and connect the latter in series with a switch and the DC supply line. Is there any deflection of the galvanometer when the switch is closed or opened? **DO NOT LEAVE THE SWITCH IN THE CLOSED POSITION.** Without changing any electrical connections to the two coils arrange them side by side so that you can insert the U-shaped piece of iron into the coils. Now try closing and opening the switch. Can you explain your observation remembering that μ_0 in the formulae quoted in the introduction refers to coils placed in a region of space where there is only a vacuum (or air)? This arrangement of the two coils with no electrical interconnection is essentially a crude transformer. Explain why transformers are only used in AC circuits, where the current and voltage change with time.

Part B - Measurement of Induced Voltage

INTRODUCTION

Our problem is to measure the induced voltage V generated in a coil by a changing magnetic flux. From Faraday's Law we know that the voltage induced in a closed loop of N_1 turns through which the flux is changing is given by

$$V = N_1 \frac{d\phi}{dt} \quad (1)$$

where $N_1\phi$ is the total flux passing through that loop. If the loop is small enough so that B is essentially constant over the area A_1 of the loop, then

$$\phi = B A_1 \cos \theta \quad (2)$$

whence

$$V = N_1 A_1 \cos \theta \frac{dB}{dt} = N_1 (\pi R_1^2) \cos \theta \frac{dB}{dt} \quad (3)$$

where θ is the angle that B makes with the normal to the area. We will use a 1000-turn search coil having an average radius of $R = 2.5\text{cm}$.

The field B is generated by a large 400-turn coil (i.e. $N_2 = 400$) carrying a 60 Hz AC current I , given by

$$I(t) = I_0 \sin \omega t = I_{rms} \sqrt{2} \sin \omega t \quad (4)$$

where $I_{rms} = I_0/\sqrt{2}$ is the reading of the ammeter and $\omega = 2\pi f = 120\pi$. The factor $\sqrt{2}$ is present because the peak value of the current is that much greater than the RMS value which the ammeter gives.

If the search coil is placed near the large coil, an emf or voltage will be induced in the search coil. If the large coil has a current, given by equation 4 then there will be a magnetic field at the center of the large coil (see Introduction). Thus, if the search coil is placed at the center of the large coil, there will be a (changing) magnetic flux in the search coil, and the amplitude of the induced voltage will be given by

$$V = N_1 \pi R_1^2 \frac{\mu_0 N_2}{2R_2} I_{rms} \sqrt{2} \omega \cos \theta \quad (5)$$

where N_1 , R_1 , N_2 , and R_2 are the number of turns and radius of the small and large coils, respectively, whereas θ is the angle between the direction of B and the normal to the area of the small coil. It has been assumed that the frequency of the current is 60 Hz (60 cycles per second), so that $\omega = 2\pi \cdot 60$ Hz.

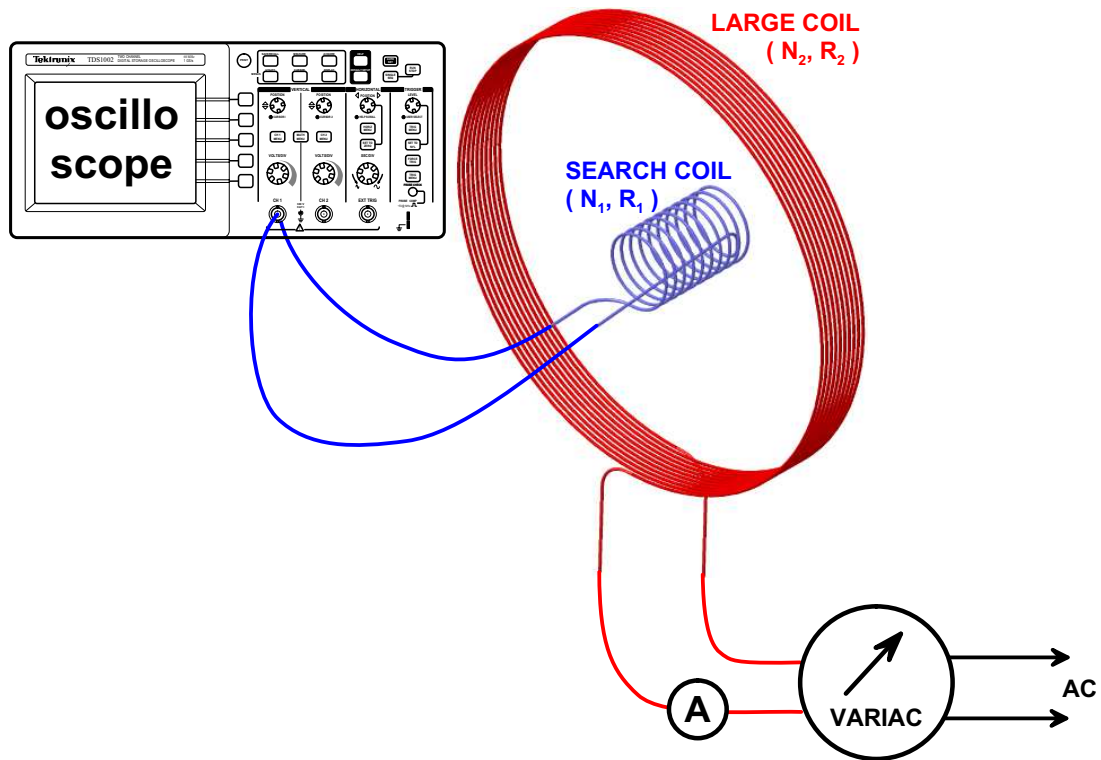


Figure 1 Entire Apparatus.

PROCEDURE

Note: Holes on the plate for placement of the search coil are spaced 5 cm apart, Diameter of large coil is 48.40 cm.

The variac, which is a device for controlling the AC voltage, should be connected in series with the large coil and an AC Ammeter. Before turning on the power, check to see that the dial on the variac is set for a minimum value. After the power is on, slowly increase the setting until the AC ammeter reads 1 A. Note that the reading on the ammeter is affected by its proximity and orientation with respect to the large coil. Attempt to position the meter so that this effect is a minimum.

Now connect the leads from the search coil to the oscilloscope.

1. Place the search coil in the center of the large coil and record the voltage for various angles of orientation from 0 to 90 degrees.

2. Record the voltage for various positions along the axis of the large coil being careful to keep the planes of the two coils always parallel.

ANALYSIS

1. Compare the observed voltage with the computed value of the induced voltage from equation 5 when the search coil was placed at the center of the large coil. Plot the observed voltages against the angles and compare this curve with a cosine curve.
2. If time permits, plot the induced voltage against the displacements along the axis. Is this curve consistent with the appropriate formula in your text?

Questions (to be answered in your report):

1. Explain why the ammeter reading was affected by the large coil.
2. What error is there in assuming $\phi = B A \cos \theta$?
3. Use Faraday's Law and the equation for the flux at the center of a large circular loop to derive equation 5. What is the mutual inductance K for the search coil and the large coil?