

## Magnetic induction

**Goal:** To become familiar with magnetic induction, Faraday's law, and Lenz's law through a series of qualitative and quantitative investigations.



### Lab Preparation

Magnetic induction refers to phenomena where a changing magnetic field induces an electric field, and possibly an electric current or a voltage in a nearby conductor. For example, waving a permanent magnet near a loop of wire will induce an electric current in the loop. This induced current itself creates a magnetic field. The induced magnetic field tends to keep the total magnetic flux through the loop constant - the induced current flows so as to oppose the change in magnetic field that causes it. This is the essence of Lenz's law. If the loop is opened and a voltmeter attached, the induced voltage or electromotive force (EMF) that will cause the current to flow can be measured. Faraday's law relates the rate of change of magnetic flux and the induced voltage drop around the loop:

$$\mathcal{E} = - \frac{\Delta\Phi}{\Delta t}$$

For uniform magnetic fields, the magnetic flux through one loop of wire is

determined by the area of the loop and the component of  $B$  perpendicular to the plane of the loop. The flux is given simply by

$$\Phi = BA \cos \theta$$

where  $B$  is the magnetic field's magnitude and  $A$  is the area of the loop.  $\theta$  is the

angle between the  $B$  field and a vector that is perpendicular to the plane of the loop as shown in Figure 1.

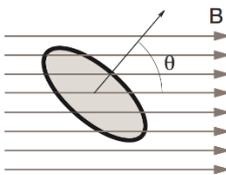


Figure 1

If no magnetic field lines cut through the area of the loop (e.g.  $\theta = 90^\circ$ ), the magnetic flux is zero. When a coil consisting of  $N$  turns replaces the single loop, the flux through the coil is  $N$  times larger.

If the magnetic field oscillates in time between  $+B_0$  and  $-B_0$  with a linear time dependence as in Figure 2,

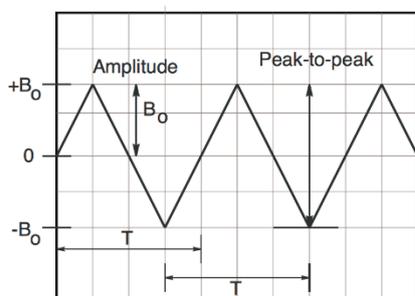


Figure 2: Oscillating magnetic field with amplitude  $B_0$  and period  $T$  ramps linearly from  $-B_0$  to  $+B_0$  in half a cycle, then back to  $-B_0$  in a triangle wave pattern.

the magnetic flux will have the same time dependence,  $\Phi(t) = A \cos \theta B(t)$ , and the induced voltage will be

$$\begin{aligned} \mathcal{E} &= -N \frac{\Delta \Phi}{\Delta t} \\ &= -NA \cos \theta \frac{\Delta B}{\Delta t} \\ \mathcal{E} &= \pm \frac{4B_0}{T} NA \cos \theta \end{aligned}$$

The sign of the induced voltage will depend on whether the field is increasing or decreasing. This result shows you can find the amplitude of the magnetic field by solving the previous equation for  $B_0$ , and measuring the amplitude,  $E$ , of the alternating voltage induced in the detector coil:

$$\text{Equation 1: } B_0 = \frac{\mathcal{E}T}{4NAC\cos\theta}$$

In this lab you will first carry out a set of qualitative observations of the current induced in a small detector coil when a permanent magnet is moved. Then you will make quantitative measurements of the induced voltage and use Faraday's law to infer the strength of an oscillating magnetic field produced by a larger coil of wire. You will investigate various aspects of Faraday's law and measure the strength of the magnetic field as a function of distance from the field-producing coil.

## Equipment

A galvanometer is a device that detects current. The galvanometer used in this lab has three ranges of increasing sensitivity. It shows the direction of the current by the direction of deflection of its needle. A positive current (i.e. entering the meter at the + terminal and flowing out the - terminal) causes a positive (rightward) deflection. Currents flowing in the opposite sense will cause an opposite deflection. To use the galvanometer, one of the three range buttons must be pressed (and held) to complete the circuit. Always begin measuring with the least sensitive range (usually #1). If little or no deflection is observed, try successively more sensitive ranges.

## Procedure

### I. Qualitative observations with a permanent magnet and detector

A. A permanent bar magnet with poles labeled N and S is provided, along with a galvanometer and two detector or pick-up coils on long handles. Begin with the detector coil consisting of 400 turns of copper wire mounted on the end of a plastic handle and two sockets for banana plug cables. Connect the detector coil and galvanometer in a simple circuit as shown in Figure 3. Pay careful attention to the legend on the detector coil showing the direction of winding of the wire in the coil (the direction shown in the figure may be different than your actual coil).

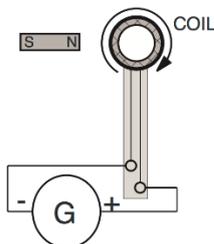


Figure 3

Wave the permanent magnet near the detector coil. (Be sure to begin with the least sensitive galvanometer scale and try more sensitive scales as needed.) Try moving the magnet from side to side over the coil and also toward and away from the detector coil. Try moving the magnet at different speeds. Answer the following:

1. What kinds of motion induce the largest current in the coil?
2. What happens if the magnet is held fixed and the detector coil is moved instead?

Before proceeding any further, discuss among your lab team whether or not your observations are qualitatively consistent with the claim that the induced current is proportional to the rate of change of magnetic flux.

B. Carry out a more systematic study of the direction of the induced current and of the consequent induced magnetic field. Begin by making some predictions as outlined below. Record your predictions with supporting diagrams before you make any measurements.

Prediction 1:

Prediction 2:

Prediction 3:

Prediction 4:

As the N pole of the magnet is brought closer to the detector coil (oriented so that it could pass through the central hole of the coil), do you expect the magnetic flux cutting through the detector coil to increase or decrease? Consider these questions in developing your prediction: Do magnetic field lines point away from or toward the N pole of a permanent magnet? How does the magnetic field strength vary with distance? Include a diagram showing your magnet and coil.

According to Lenz's law, the induced current that flows produces a magnetic field that opposes the change in flux from the approaching magnet and tries to keep the total magnetic flux constant. What direction must this induced magnetic field point to do this? Once again, show a diagram of your magnet and coil to help show your prediction.

In which direction must the current flow around the loops of the detector coil to produce this induced magnetic field? (Recall the right-hand rule that relates the direction of the current in a wire to the direction of the magnetic field produced by the current in the wire.)

Which way should the galvanometer deflect as the N pole approaches your detector coil? (Trace out the flow of current through the circuit carefully to make sure your circuit is wired appropriately. When the current flows through the galvanometer from red terminal to black, the meter will exhibit a positive, rightward, deflection.)

Prediction

5:

C. Performing the experiment.

What should happen as the magnet is pulled away?

1. Try the experiment and compare the observed galvanometer deflection to your predicted deflection. If your observations disagree with your predictions (1) re-think your predictions, discussing them with your lab instructor if necessary, and (2) verify that you have correctly related the galvanometer deflection to the direction the current flows around the loops of the detector coil, double-checking your wiring carefully.

2. What should happen if you repeat this process using the S pole of the magnet instead? Verify your predictions.

3. Replace the 400-turn detector coil with the 2000-turn coil and try a couple of the experiments. Are any differences apparent with this detector coil?

## II. Quantitative study of the induced voltage

A larger diameter coil (the “field coil”) will be used to produce a magnetic field. By driving an alternating current through the field coil, the magnetic field will oscillate in strength and direction. A detector coil placed near the field coil will then sense a time-varying magnetic flux.

A circular loop (radius  $R$ ) of wire carrying a current ( $I$ ) produces a magnetic field at its center:

$$B = \frac{\mu_0 N_f I}{2R}$$

where  $N_f$  is the number of turns and  $\mu_0 = 4\pi \times 10^{-7}$  Tm/A (see Figure 4).

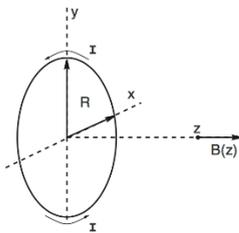


Figure 4

If  $I$  depends on time, the magnetic field exhibits the same time dependence and produces what is shown in Figure 2 in the lab preparation section.

A. Creating an oscillating magnetic field of known strength. The field coil used here has  $N_f = 200$  turns of #22 wire with an average radius of  $R = 10.5$  cm.

1. Calculate the current needed to produce a  $4.00 \mu\text{T}$  magnetic field at the center of the field

coil using  $B = \frac{\mu_0 N_f I}{2R}$ .

2. A  $1.20 \text{ k}\Omega$  resistor ( $R_S$ ) is in series with the coil, built in to the coil apparatus, as shown in Figure 5. By measuring the voltage drop,  $V_R$ , across this resistor, the current can be found from Ohm's law:  $I = V_R/R_S$ . Calculate the corresponding voltage drop  $V_R$  that is required to have a  $4.00 \mu\text{T}$  magnetic field.

B. Measuring the induced voltage. Connect the field coil, function generator and oscilloscope in the circuit shown in Figure 5. This is tricky to set up and you may need your lab instructor to help you. Set the function generator for a triangle wave with a frequency of  $f = 1/T = 500$  Hz. Using the oscilloscope to monitor the voltage drop across  $V_R$ , adjust the function generator

amplitude until  $V_R$  oscillates between  $\pm$  the calculated value (part A, #2) so that the “peak-to-peak” (from minimum to maximum) voltage is twice your calculated  $V_R$ . The magnetic field at the center of the coil is then oscillating between  $\pm 4 \mu\text{T}$ . Since  $V_R \propto I \propto B$ , the oscilloscope display of  $V_R(t)$  is in phase with and directly proportional to the magnetic field,  $B(t)$ .

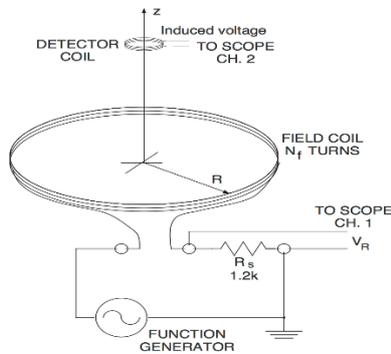


Figure 5

C. Predicting the induced voltage. Faraday’s law can be used to relate  $B_0$  to the voltage induced,  $E$ , when a detector coil is brought near the field coil. This is shown in **Equation 1**.

1. Use the Oscilloscope to measure  $B_0$  and  $T$ . The  $B_0$  can be measured using the vertical scale since  $1 \text{ V/div} = 1 \mu\text{T/div}$ . The period  $T$  can be

measured using the horizontal scale.

2. Use **Equation 1** to calculate  $E$  (which is equal to the rate of change of magnetic flux) if you put the 2000 turn detector coil at the center of the field coil with the planes of both fields and detector coils parallel ( $\theta = 0$ ). Assume the field is uniform across the small detector and that the detector coil has an area of  $6.62 \text{ cm}^2$ .

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D. Connect the 2000 turn detector coil to the second channel on the oscilloscope and position the detector coil at the center of the field coil with the planes of the coils parallel. Add a  $10 \text{ k}\Omega$  resistor in parallel with the detector coil. (A resistor for this purpose is mounted on a banana plug adapter. This damps out oscillations that may occur in the detector circuit.) Observe on the oscilloscope the voltage induced in the detector coil (CH 2) and the magnetic field (indirectly, via  $V_R(t)$  on CH 1) simultaneously (note, you may have to adjust the detector voltage to get it the voltage show up on the screen). Make a quantitative sketch of two cycles of both  $V_R$  and the voltage induced in the detector coil. Be sure to indicate the scale for each trace.

E. Carefully measure the amplitude of the induced voltage ( $E =$  one-half the peak-to-peak value observed on the oscilloscope). Compare your measured value to your predicted value.

F. (optional) Angular dependence. Tilt the detector coil, changing  $\theta$ , and observe the effect of the orientation of the coil on the induced voltage. Measure the amplitude of the induced voltage as a function of angle for  $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ$ , and  $90^\circ$ .

G. (optional) Frequency dependence.

1. Predict what will happen to the induced voltage in the detector coil if the frequency of the function generator driving the field coil is doubled to 1.00 kHz. What should happen if the frequency is reduced to 250 Hz? Briefly explain your reasoning. Recall that the period is related to the frequency by  $T = \frac{1}{f}$ .

2. Carry out the measurements. Record the amplitude of the induced voltage,  $E$ , for each frequency. Note: You may need to adjust the function

generator's amplitude control to keep the amplitude of  $V_R(t)$  – and therefore  $B(t)$  – the same at all frequencies.

**\*When finished with your lab clean up your lab station. Homework**

In part II, do part G, #1 if not done already in lab.