MAGNETIC INDUCTION

INTRODUCTION

Thus far the course and the labs have been concerned with static electric fields, steady electric currents, and static magnetic fields. This set of experiments demonstrates the interplay between electricity and magnetism when one or the other phenomenon is time-varying.

An adequate treatment of the complete theory of electromagnetic induction is beyond the scope of this lab manual; the course textbook, as well as any other introductory physics textbook, can be consulted for a full understanding of the subject. Nonetheless, we will cover two important concepts required for the lab: *magnetic flux* and *Faraday's law of induction*.

Magnetic Flux

Magnetic flux is defined as the integral of the normal component of a magnetic field passing through a surface. We can write the total flux, Φ, as the dot product of the magnetic field vector, $\vec{\mathbf{B}}$, with the area vector, $\vec{\mathbf{A}}$:

$$\Phi = \mathbf{B} \bullet \mathbf{A} = BA\cos\theta \qquad (38)$$

where θ is the angle between the field and the area vector. In the above equation, the assumption is that the magnetic field is uniform and the area is flat – this will be the case for the lab. The more general equation is:

$$\Phi = \int_A \mathbf{B} \bullet d\mathbf{A} \qquad (39)$$

The direction of an area vector $\mathbf{A}$ is simply the normal to the plane of the area (or flat surface):

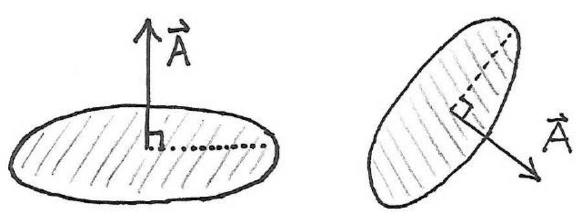


Figure 36. Area vectors for surfaces in different orientations.

If we imagine a closed loop in a constant magnetic field, we see that the flux will be at a *maximum* when the magnetic field is *parallel* to the area vector (θ = 0, 180°). It will be at a *minimum* when the field is *perpendicular* to the area vector (θ = 90, 270°). Possible loop configurations and their corresponding flux are shown in Figure 37.

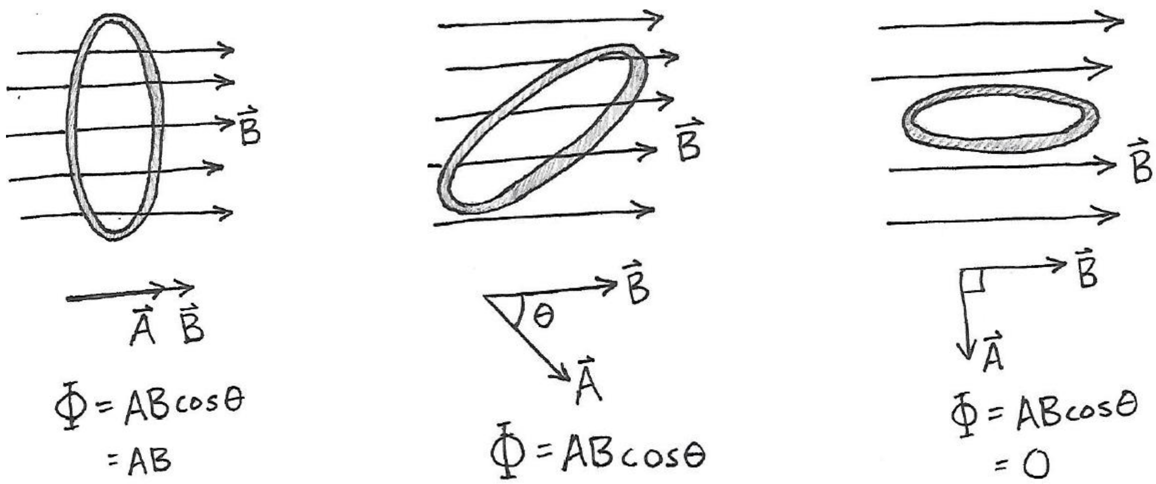


Figure 37. Magnetic flux for a closed loop in a magnetic field. *Left:* The magnetic field and area vector are parallel, so the flux is at a maximum. *Middle:* The magnetic field and area vector are at an angle θ, so the flux scales as the cosine of that angle. *Right:* The magnetic field and area vector are perpendicular, so no field lines go through the loop (the flux is 0).

Now that we've gone over magnetic flux, let's examine what happens when the flux *changes*.

Faraday's Law of Induction

The magnetic flux through a closed curve can change in several ways; for example, the loop can be placed into or removed from a magnetic field, the angle between the loop area and the magnetic field can vary, or the magnetic field can be made to vary in strength and/or direction. These flux changes are not without consequences.

Any change in the magnetic flux through a closed curve results in a voltage being induced along that curve: We call this voltage the *electromotive force*[24] or "*emf*". We can measure this voltage using a voltmeter or oscilloscope connected to an *open*-ended conductor (wire) that follows the curve (see Figure 38). Alternatively, with a *closed* conductive loop, a current will flow[25] as a result of the *emf.* In this lab we will only be studying the former configuration; *i.e.* an o*pen* loop connected to a sensor.

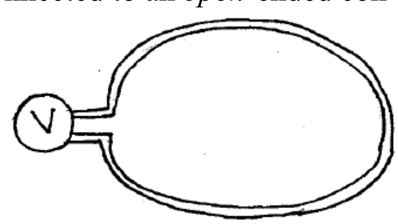


Figure 38. An open loop with a voltmeter.

Magnetic induction can be best summarized by Faraday's law:

$$emf = -\frac{d\Phi}{dt} \tag{40}$$

[24] Note that the *emf* is not an actual *force* measured in Newtons; it is a *potential difference*, measured in volts.

[25] A current will only flow if the loop is 1) closed and 2) made of conducting material. If the loop is not closed (as in Figure 38), an *emf* will be induced, but no current will flow.

The right hand side of Equation (40) refers to the rate of change of the magnetic flux through a loop or surface[26]; and the left hand side refers to the electromotive force that is induced around the boundary line of the loop or surface. You can think of the negative sign as indicating that the magnetic field induced by the *emf* will point in the opposite direction as the change in the applied magnetic field. An example is given in Figure 39 below for a closed loop:

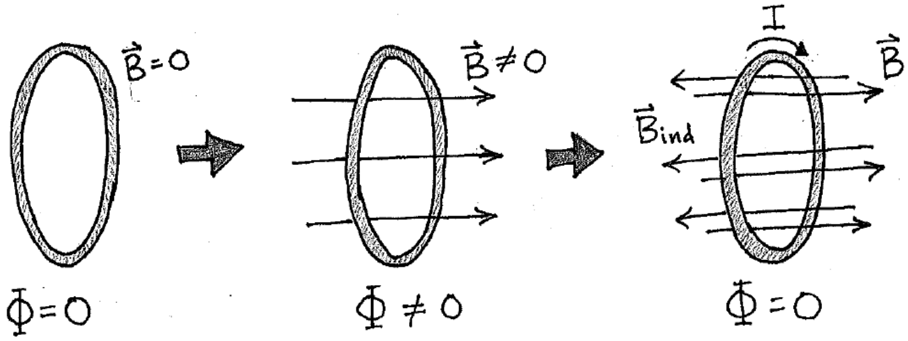


Figure 39. A closed wire loop is initially in zero applied field, $\vec{\mathbf{B}}=0$, with a corresponding magnetic flux of 0. When an increasing magnetic field is applied which points to the right, the magnetic flux is correspondingly increased, resulting in an *emf*; which, in turn, results in an induced current *I*, which in turn produces a magnetic field opposite to the applied field.

Rewriting Equation (40) as

$$emf = -\frac{d}{dt}(BA\cos\theta) \tag{41}$$

we see that an *emf* can be induced in our detector coil when we vary one or more of these three quantities over time:

1. **The angle (θ),** by varying the orientation of a loop of wire in the neighborhood of a static magnetic field. (This is the principle of the electric generator and of the automotive alternator).
2. **The external field (B):**
    a. By electronically varying the ambient magnetic field, but keeping the loop of wire fixed in place. (This is the principle of the transformer).
    b. By moving a permanent magnet in the vicinity of a stationary loop of wire (this is the principle of the credit-card swipe). We can also move our loop of wire in and out of a magnetic field.
3. **The area (A)**, by changing the size of the wire loop (we unfortunately cannot do this with our apparatus).

THE EMF INDUCED IN A FIXED COIL BY A MOVING MAGNET

In this experiment we will study the *emf* generated by the motion of a permanent magnet through a coil. In this and subsequent experiments we will be using the Tektronix TDS 210 oscilloscopes. If you do not remember how the controls work, please refer to Appendix B in this manual.

[26] This can be any open surface in space, such as a thin disc, a portion of a sphere, or a butterfly net. An example of a very simple surface would be a thin, flat disc of radius a, bounded by a circle of radius a.

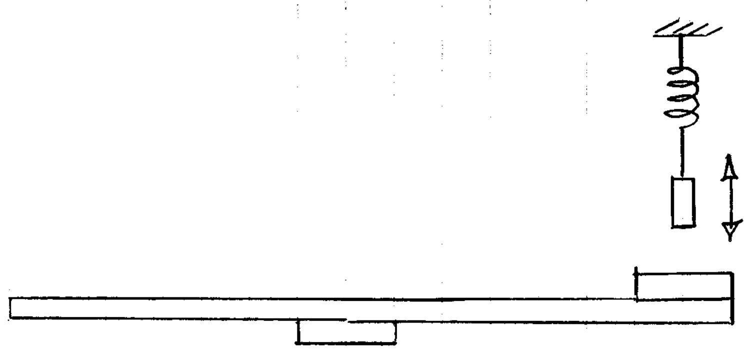


Figure 40. The detector coil and spring-suspended magnet.

The detector coil (see Figure 40) consists of wound copper wire attached to a handle. Each end of the wire is connected to one of the terminals on the banana jacks. When an *emf* is generated in the coil of copper wire, the corresponding voltage is recorded by the oscilloscope. A large, abrupt change in magnetic flux will result in a large jump in voltage.

Experiment 1

1. **Set up the detector:** Connect the detector coil to Channel 2 of the oscilloscope. On the **CH 2** menu, set the **Coupling** to **DC**.[27] The vertical sensitivity (**VOLTS/DIV**) should be 200 - 500 mV/division. Set the horizontal trace (**SEC/DIV**) to 250 ms/division. On the **TRIGGER** menu, set **SOURCE=CH2**, and **MODE=AUTO**.
2. Give the magnet a slight tug, so that it executes small oscillations. Explain the signal that you observe on the oscilloscope.

MOVING LOOP IN A STATIC MAGNETIC FIELD

In this section, we will experiment with rotating or moving a loop of fixed area in a magnetic field. As the angle θ between the loop and the field changes, the magnetic flux intercepting the loop will change (see Figure 37), and an *emf* will be induced in the loop.[28] This is the principle of the electric generator and of the electric alternator.

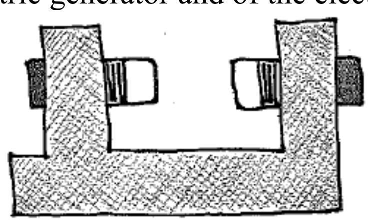


Figure 41. Strong permanent magnet (side view). The separation between the two poles is adjustable.

[27] We will abide by the custom of using Channel 2 of the oscilloscope for measuring the response of our system.
[28] These experiments are similar to Experiment 1. However, in Experiment 1 we moved the magnet; in this experiment we move the detector.

Experiment 2

In this experiment you will use the strong permanent magnet (Figure 41) at your bench. The detector coil and oscilloscope settings are the same as for Experiment 1. If the coil is stationary, there should be no signal recorded by the oscilloscope.

1. Quickly rotate the detector coil so that its axis is alternately parallel and perpendicular to the axis of the permanent magnet. Observe the pulse shape and amplitude on oscilloscope. How does changing the orientation of the field change the pulse shape?
2. With the detector coil axis parallel to the main magnet axis, move the detector coil alternately away from, and into, the magnet gap. Record the pulse shape and amplitude from the oscilloscope.

FIXED LOOP IN A VARIABLE MAGNETIC FIELD

In this experiment we will electronically control a magnetic field by connecting a time-varying current source to a coil. We will use a triangular waveform, so that at any given moment, the current is either uniformly increasing or decreasing. We will then use a nearby detector coil to measure the induced *emf*. The resulting phenomena serve as the basis for the alternating-current transformer.

To set up the magnetic flux source and detector coil: With banana cables, connect the signal generator to the main coil (see Figure 42) and also to Channel 1 of the oscilloscope. Connect the detector coil to Channel 2 of the oscilloscope.

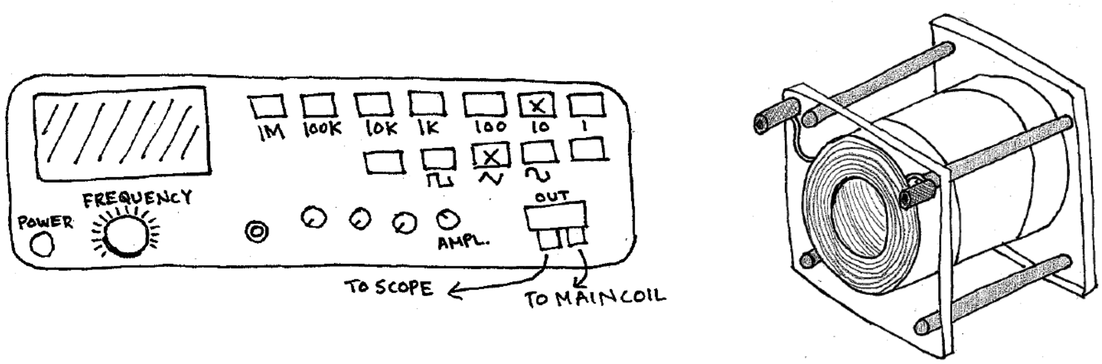


Figure 42. Signal generator (left) and main coil (right).

On the oscilloscope:

1. Set the **Trigger Input** to **CH 1** and set the **Trigger Mode** to **Normal**.
2. Set the vertical sensitivity for Channel 1 to about 2 V/division.
3. Set the vertical sensitivity for Channel 2 to about 50 mV/division (you may need to adjust this over the course of the experiment).
4. Set the horizontal trace to around 100 ms/division.

On the signal generator:

1. Set the signal generator waveform to triangle wave.
2. Set the signal generator frequency to about 2 cycles/second (Hz).
3. Set the amplitude of the signal generator to between 5 and 10 volts.

If all of this has been done correctly, you will observe a triangle waveform on Channel 1 of the oscilloscope, representing the voltage across the coil. Channel 2 will show the induced *emf* in the detector coil.

> Note: If you are seeing tremendous noise on Channel 2, it is probably because you are picking up noise emitted by the oscilloscope. The cure is easy: make sure the oscilloscope is far away from the probe.

Since the main coil providing the flux is effectively a resistor, the current waveform will also be a triangle waveform. Thus, the magnetic flux will also be a triangle wave. This means that the magnitude of the current, and therefore the magnitude of the magnetic field, is always changing at a constant rate, albeit with alternating sign.

Experiment 3

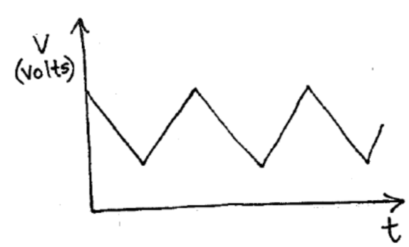
To test the direction of the magnetic field, put the Magnaprobe into the center of the main coil. How does it behave? Try varying the frequency between 0 and 3 Hz, and observe how the magnetic field direction changes with time.

Now set the signal generator frequency to about 5 Hz. With the detector coil close to, and initially coaxial with, the main coil, perform and interpret the following:

1. What is the observed waveform of the detector coil on the oscilloscope? Sketch the input (Channel 1) and output (Channel 2) signals. You may find it helpful to freeze the image on the scope by pushing the RUN/STOP button on the upper right.
2. What happens when you reduce the frequency of the signal to 2.5 cycles per second?
3. What happens when you move the coils farther apart?
4. What happens when you place the axis of the detector coil at right angles to the axis of the main coil?

PRE-LABORATORY

In Experiment 3, a triangle waveform is applied to the source coil. The voltage (and corresponding current) alternately increases with time at a certain rate, and then decreases with time at the same constant (negative) rate, repeating the cycle at some frequency *f*. A visual is shown to the right.



a) Reproduce the sketch shown here, and below it draw the expected magnetic field versus time.
a) Just below that sketch, draw (qualitatively), the magnetic flux Φ intercepting the detector coil versus time.
b) Just below this sketch, draw (qualitatively) $d\Phi/dt$. This will be your predicted waveform for the *emf* of the detector coil.