

## PHY 112L Activity 6

### Faraday's and Lenz's Laws: Electromagnetic Induction and Magnetic Flux

Name: \_\_\_\_\_

ID #: \_\_\_\_\_

Section: \_\_\_\_\_

Date: \_\_\_\_\_

Lab Partners: \_\_\_\_\_ TA initials: \_\_\_\_\_

#### Objectives

1. Introduce electromagnetic induction and magnetic flux
2. Investigate Faraday's Law and Lenz's Law for a solenoid
3. Compare calculated and experimentally determined values for the flux of a solenoid (lab report)

#### Materials & Resources

1. Computer with DataStudio and Pasco voltage and magnetic field sensors
2. Bar magnets and solenoid

#### Introduction

It was shown in the previous lab that a current flow creates a magnetic field that depends on the current's strength and configuration. Similarly, in this lab we will use a magnetic field to generate a current in a given wire configuration.

To understand this, we must first understand magnetic flux. The magnetic flux,  $\Phi$ , is defined as the strength of the magnetic field component that passes straight (perpendicular) through an area enclosed by a wire times that area; this is illustrated in Figure 1 and can be expressed mathematically as:

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

where  $B$  is the magnetic field strength,  $A$  is the area enclosed by wire, and  $\cos\theta$  is the factor that takes into account the direction of the magnetic field lines relative to the area created by the wire. When  $\theta = 0^\circ$  ( $B$  is perpendicular to  $A$ ), then  $\cos\theta = 1$  and  $\Phi = BA$ . The SI unit for the magnetic flux is the weber (Wb).

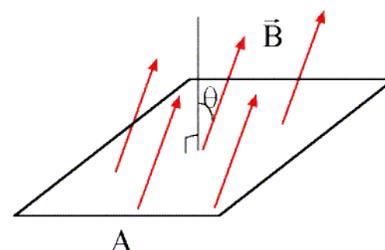


Figure 1

It is important to note that a stationary (not moving in space or time) magnetic field will not create a current by inducing a voltage; only a magnetic field that is changing with respect to time or has motion relative to a particular wire configuration is able to generate a current within that wire. This is known as Faraday's law, and for a wire coil with  $N$  loops; this is illustrated in Figure 2 and can be expressed mathematically as:

$$V = -N \frac{d\Phi}{dt} \approx -N \frac{\Delta\Phi}{\Delta t}$$

which states that the induced voltage,  $V$ , is proportional to the rate of change of the magnetic flux,  $\Phi$ , times the number of loops,  $N$ . The negative sign in Faraday's law arises from the fact that the loop *resists* the changes due to the magnetic flux. The current induced in a loop by a magnetic field flows in a direction that generates a magnetic field whose flux *opposes* the change in the original flux. This property is known as Lenz's law.

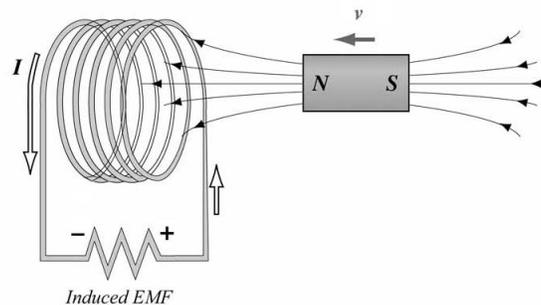


Figure 2

# 1. Properties of Magnetic Induction (Faraday's and Lenz's Laws)

## Procedure:

- 1) Setup the solenoid with a voltage sensor and magnet as shown in Figure 3, open a new experiment in DataStudio, select a voltage sensor for the appropriate channel, and set the sample rate to 200 Hz, as shown in Figure 2. Open a graph that displays voltage vs. time and maximize the graph's view window.
- 2) Click Start in DataStudio and move the magnet relative to the solenoid as shown in Figure 5. Try to understand how the graph is representing the motion of the magnet; pay particular attention to what happens as you change the speed of the magnet, flip its polarity, or use the other end of the solenoid, which is essentially equivalent to reversing the leads to the voltage sensor. Each person in the lab group should take a turn moving the magnet until they understand these 3 basic features. If the data on the graph becomes too small to see well, then you may click Stop and then Start to reset data collection; you may also completely clear the data by selecting "Delete All Data Runs" under the Experiment tab as many times as you need.
- 3) Clear all data from the graph, hold the magnet by covering the "S" with your thumb (like a wand), Click Start again, *carefully* insert the "N" end of the magnet into the side of the solenoid with the positive (red) voltage lead, as shown in Figure 3, then remove the magnet from the solenoid *very* quickly. Be sure to insert the magnet as far as you can, and remove it as quickly as you can. Then flip the magnet so that you are holding the "N" side, repeat this process, and click Stop. Enlarge and enhance the view of your data by adjusting the axis locations and scales so that the relevant data takes up the whole graph window, and then print this graph.
- 4) Flip the polarity of the voltage sensor moving the red and black leads or simply by turning the solenoid so that the black voltage lead is on the left in Figure 3 above. Precisely repeat step 3 with this new voltage polarity and print the second graph too.

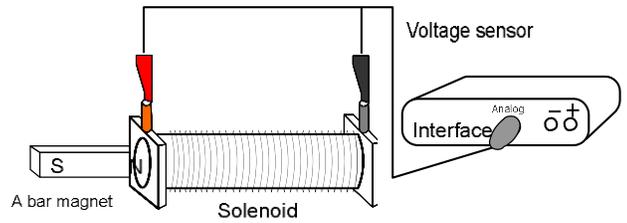


Figure 3

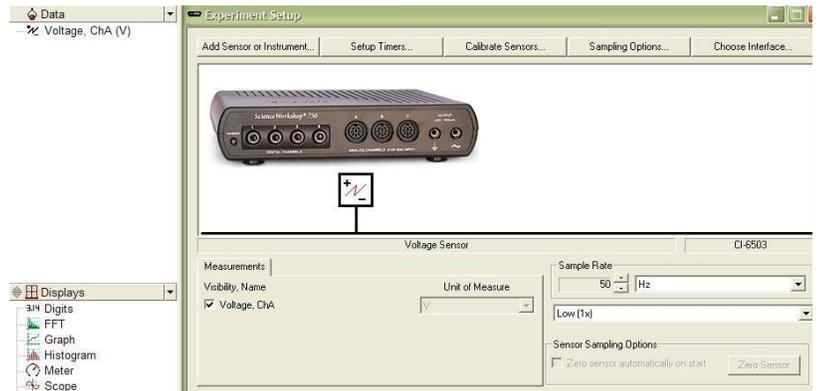


Figure 4

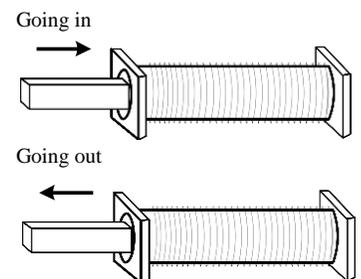


Figure 5

## Questions:

- 1) Faraday's law says that the voltage induced in a wire is proportional to how fast the magnetic flux is changing. Explain how the data in your graphs illustrates this law below. Hint: think about the relationship between the peak voltages on the graph and how fast the magnet was moving when that data was collected by the sensor.
- 2) Faraday's law also implies that the voltage induced in the solenoid as the magnet is inserted is equal and opposite the voltage induced as the magnet is removed. Do your graphs support this? Carefully justify your answer below.
- 3) Lenz's law says that the voltage induced in a wire by a changing magnetic flux creates a current in the wire that generates a new magnetic field whose flux opposes the change in the original flux, hence the negative sign in Faraday's law. List all 3 ways that your graphs represent Lenz's law below. What caused the voltage output to flip?

## 2. Electromagnetic Induction and Magnetic Flux

### Procedure:

- 1) Delete all data from part 1, and then setup the solenoid as shown in the Figure 6. You will be measuring the induced voltage as before, but this time as the magnet falls through the solenoid.

**Caution:** The magnets are quite fragile and will break if they land on the floor or a hard desk. Allow the magnets to fall completely through the solenoid and land on something soft like a backpack or the chair seat.

- 2) Click Start, let the magnet fall through the solenoid from about 1 cm above the opening, then click Stop. Be sure to release the magnet carefully and that the solenoid is vertical so that the magnet falls straight through with negligible contact. Also ensure that the magnet has enough room to fall all of the way through the solenoid before it lands.
- 3) Verify that your Voltage vs. time curve resembles that shown in Figure 7. If it does not, then delete this data run and repeat step 2 until it does.
- 4) Since the strength of the induced voltage is given by

$$|V| = N \frac{d\Phi}{dt}$$

Then the magnetic flux per turn of the solenoid can be written as

$$\Phi = \int t/V / N$$

where  $N = 1340$  is the number of turns on the solenoid and  $\int t/V$  is equivalent to the area under the Voltage vs. time curve.

- 5) In order to find the area under the Voltage vs. time curve, carefully highlight your data as shown in Figure 8. Be sure to grab the entire “tail” of the curve, as well as all of the data up to the  $V = 0$  mark, where the voltage becomes positive again. Note: unless you have a data point precisely on the t-axis, you will either have to stop highlighting at the data point just before or just after the voltage becomes positive. For best results, choose the data point that is closest to the t-axis as your last highlighted data point. Then select “Area” from the “ $\Sigma$ ” drop-down menu. A box should appear with a calculated value for the area under the highlighted portion of the curve. Record this value in the table, and then calculate  $\Phi$  using the formula above and record as well.

- 6) Verify that the area under the positive side of this curve is approximately equal to your value from the negative side. Highlight this side in a similar way and verify that the reading for Area on the graph equals  $A_1$ ; print this graph.

- 7) Repeat steps 2 – 5 four more times and record your results in the table.
- 8) Select a “New Empty Data Table” from the “Experiment” menu, then enter your experimental values for A into the “X” column and  $\Phi$  into the “Y” column of this table.
- 9) Select “mean” and “standard deviation” from the “ $\Sigma$ ” drop-down menu; record in the table here.

### Question:

Would the areas in the graph from step 6 be equal if the magnet were dropped from 1 cm inside the solenoid? Why?

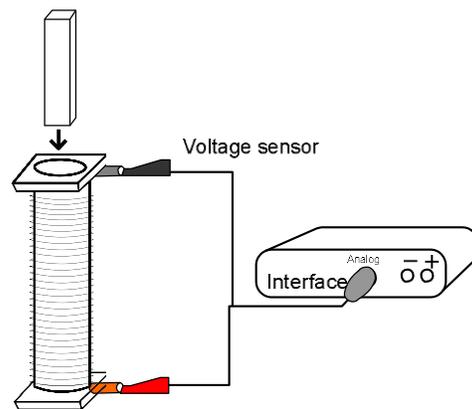


Figure 6

**Do not drop the magnet on a hard surface.**

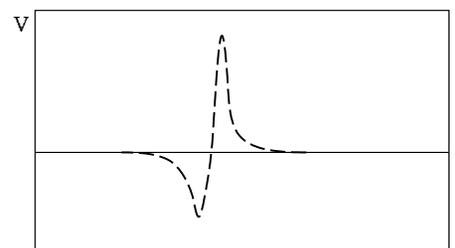


Figure 7

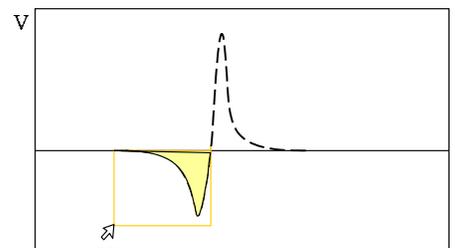


Figure 8

Trial #	Area $A = \int t/V$	Magnetic Flux $\Phi = A/N$
1	$A_1 =$	$\Phi_1 =$
2	$A_2 =$	$\Phi_2 =$
3	$A_3 =$	$\Phi_3 =$
4	$A_4 =$	$\Phi_4 =$
5	$A_5 =$	$\Phi_5 =$
Average	$A_A =$	$\Phi_A =$
Standard Deviation	$\Delta A =$	$\Delta \Phi_A =$

### 3. Direct Calculation of Magnetic Flux (Lab Report)

#### Procedure:

- 1) Disconnect the voltage sensor from the interface and solenoid and open a “New Activity” in the “File” menu; there is no need to save your previous activity. Connect the magnetic field sensor to the interface, and then verify that the sensor’s scale switch is set to “1X” and that the mode switch is set to “Axial”. Setup the magnetic field sensor in DataStudio for “1X” operation on the appropriate channel, open a “Digits” window to display the reading, and then click Start.
- 2) Hold the sensor still and away from any magnets, walls, metal, or electronic equipment, then press the tare button. Verify that the reading is stable and approximately 0. Measure the magnetic field strength  $B$  at one end of the magnet; be sure the tip of the sensor is touching the magnet and is parallel with the magnet. (See Figure 9). DataStudio displays measurements of magnetic field in gauss  $B_G$ , but values for magnetic field strength should be in teslas  $B_T$  when calculating magnetic flux  $\Phi$ . Record the magnitude of the measured value as  $B_G$ , convert this value to teslas using  $10,000 \text{ G} = 1\text{T}$ , and then record the converted value as  $B_T$  in the spaces provided below.

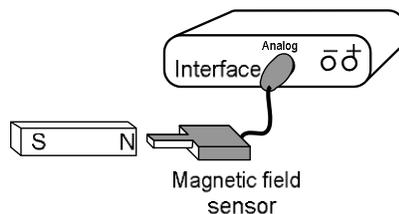


Figure 9

$$B_G = \underline{\hspace{2cm}} \pm \underline{100} \text{ ( gauss )} \quad B_T = \underline{\hspace{2cm}} \pm \underline{0.01} \text{ ( teslas )}$$

Note: the measurement uncertainty for the sensor has been given here as *value*  $\pm$  *uncertainty* ( *units* ).

- 3) Use the calipers, which have an uncertainty of 0.01 mm, to measure and record the outside diameter  $D$  of the solenoid. Be sure the calipers are perpendicular to the length of the solenoid when making this measurement. Calculate the radius  $R$  and cross sectional area  $A$  of the solenoid; record these results with correct significant figures and units.

$$D = \underline{\hspace{2cm}} \text{ ( m )} \quad R = D/2 = \underline{\hspace{2cm}} \text{ ( m )} \quad A = \pi R^2 = \underline{\hspace{2cm}} \text{ ( m}^2 \text{ )}$$

- 4) Calculate a theoretical value for magnetic flux  $\Phi_T$  using  $A$  and  $B_T$  measured above, where the angle  $\theta$  between the magnet and the normal to the cross sectional area is  $0^\circ$  since the magnet passes straight through the solenoid. Then calculate the percent difference between  $\Phi_T$  and  $\Phi_A$  measured in part 2 above; record your results in SI units below.

$$\Phi_T = B_T A = \underline{\hspace{2cm}} \text{ ( )} \quad \% \text{ difference} = \frac{|\Phi_A - \Phi_T|}{\frac{1}{2}(\Phi_A + \Phi_T)} \times 100 = \underline{\hspace{2cm}} \%$$

- 5) The measurement uncertainty for  $\Phi_T$ ,  $\Delta\Phi_T$ , is calculated using the following equation, where the measurement uncertainties for the magnetic sensor and calipers in SI units are 0.01 teslas and 0.00001 m, respectively. Substitute your measured values for  $B_T$  and  $R$  into this equation and calculate a value for  $\Delta\Phi_T$  in the space provided below.

$$\Delta\Phi_T = \Phi_T \sqrt{\left(\frac{0.01}{B_T}\right)^2 + 2\left(\frac{0.00001}{R}\right)^2} = \underline{\hspace{2cm}} = \underline{\hspace{2cm}} \text{ ( )}$$

#### Questions:

- 1) The measurement uncertainty  $\Delta\Phi_T$  is similar to the standard deviation  $\Delta\Phi_A$  calculated in part 2 above in that both provide a measure of how precise each measurement method is. According to your values for  $\Delta\Phi_T$  and  $\Delta\Phi_A$ , which method for measuring magnetic flux is more precise? Briefly justify your answer below.
- 2) Calculate values for the sum  $\Delta\Phi_T + \Delta\Phi_A = \underline{\hspace{2cm}}$  ( ) and the difference  $|\Phi_T - \Phi_A| = \underline{\hspace{2cm}}$  ( ). Which of these results is larger? Is it *valid* to compare these methods of measuring magnetic flux? Why or why not?
- 3) Recall using the *outer* diameter  $D$  of the solenoid to determine  $A$  in step 3 above. Briefly explain how this measurement could be modified to get a more accurate result for the cross sectional area of the solenoid  $A$ ?