Faraday's Law

PHYS 296

Your name____________________ **Lab section**____________________

PRE-LAB QUIZZES

1. What will we investigate in this lab?

2. State and briefly explain Faraday's Law.

3. For the setup in Figure 1, when you move the bar magnet from the right to the center of the coil, the voltmeter reads a positive voltage.

(a) When you move the bar magnet from the center of the coil to the left, does the voltmeter read a positive or negative voltage?

(b) When you move the bar magnet from left back to the center of the coil, does the voltmeter read a positive or negative voltage?

(c) For all the cases, when you move the bar magnet faster through the coil, does the induced voltage increase or decrease in magnitude?

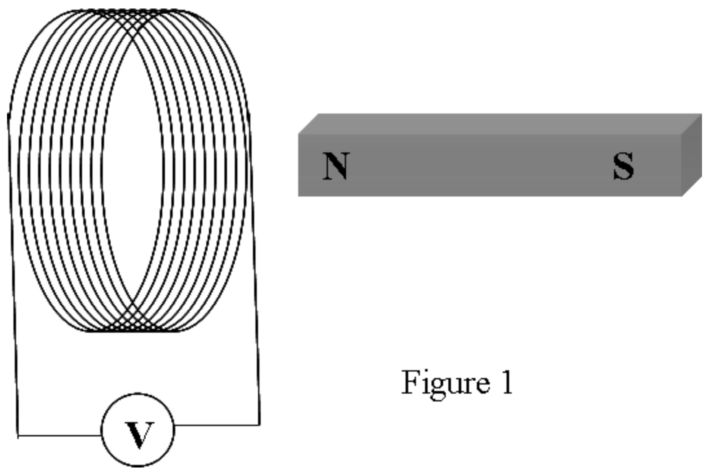

Figure 1

Faraday's Law
PHYS 296

Name____________________________ **Lab section**______________________

Lab partner's name(s)____

Objective

Investigate Faraday's law.

Background

Early in the 19th century, Joseph Henry discovered that by varying the magnetic field in a circuit one could induce electric current. In 1831, unaware of Henry's work, Michael Faraday independently and systematically conducted similar experiments with a coil and a bar magnet as shown in Figure 2a. As Faraday observed, when the bar magnet was moved towards the coil, a current was induced in the circuit. Moving the bar magnet away from the coil induced an opposite current in the circuit. When repeating the experiment with the orientation of the bar magnet reversed, the induced current also changed direction. Moreover, Faraday found that (Figure 2b) when the current of a current-carrying solenoid was changed – thus changing the magnetic field inside the solenoid – a current was induced in a second solenoid placed inside the first solenoid. Altogether, Faraday discovered that a current could be induced in a circuit by changing the magnetic field through the circuit. Faraday's work was summarized by James Clerk Maxwell, Faraday's student, in the following equation – known as Faraday's law – which relates the induced voltage in a solenoid, V, and the variation rate of the magnetic flux (Φ_B) through the solenoid

$$V = -N\frac{d}{dt}\iint_A \vec{B}\cdot d\vec{A} = -N\frac{d\Phi_B}{dt}, \tag{1}$$

where N is the number of turns of the wire in the solenoid, B is the magnetic field, and $d\vec{A}$ is an infinitesimal area element on a surface bounded by the solenoid. For example, if $B(t)$ is uniform inside the solenoid and points parallel with the solenoid and if the cross sectional area of the solenoid is A, Equation (1) becomes:

$$V(t) = -NA\frac{dB(t)}{dt}. \tag{1$'$}$$

Faraday's law is the operating principle for many devices including generators and microphones. A generalization of Faraday's law is given by one of Maxwell's equations. Fundamentally, it discloses that the magnetic field and the electric field are intrinsically related to each other. This is particularly made evident in Einstein's theory of special relativity.

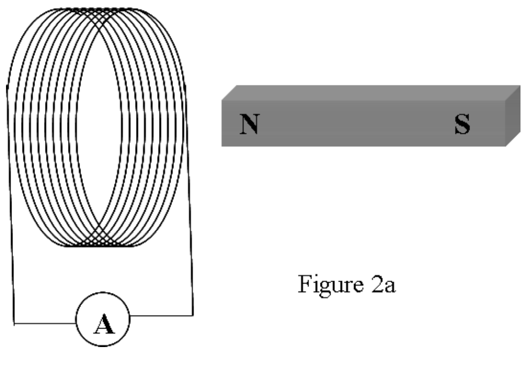

Figure 2a

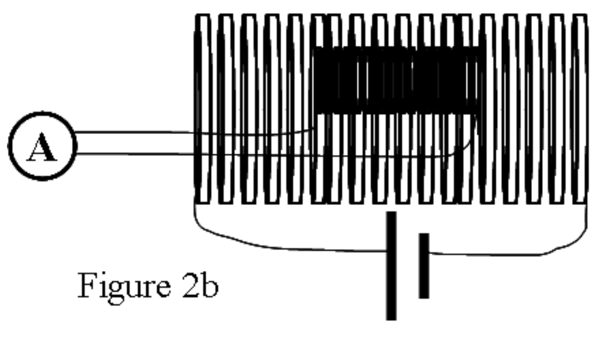

Figure 2b

PART I

In part I, we demonstrate Faraday' Law through observing the effect produced by relative motion between a coil and a magnet.

(A) Inducing voltage by moving a magnet into & out a stationary Coil

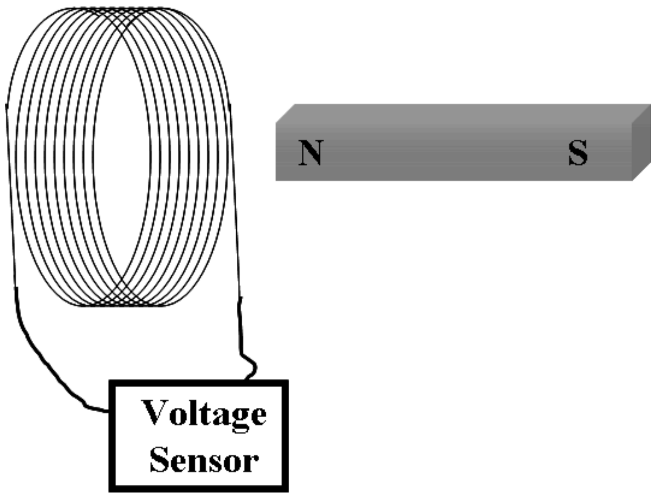

Figure 3. The setup to measure the voltage over a coil induced by changing magnetic flux.

PROCEDURES

1. Connect the two ends of the coil directly to *Input Channel A* of ***7500 Interface***.
2. In ***Data Studio***, select *voltage sensor* for *Channel A*. Set the sampling rate to 100 Hz. Open *graph display* to display *voltage-versus-time*.
3. Hold the bar magnet by one hand and click *start button* in ***Data studio***. Move the magnet back and forth slowly through the coil several times. Then, move the magnet back and forth faster through the coil several times. Again, increase the speed until the magnitude of the voltage changes significantly. Click *stop button* in ***Data studio***.

QUESTIONS

1. Using the recorded *voltage-versus-time* graph, correlate the sign and the magnitude of the induced voltage with the movement of the magnet relative to the coil and use Faraday's law to explain the correlation.

2. Based on the above observations, describe a method to increase the magnitude for the induced voltage.

(B) Inducing voltage by moving a coil relative to an stationary magnet

PROCEDURES

Repeat steps 1-3 as in Part I (A), but now you keep the magnet stationary and move the coil relative to the magnet.

QUESTIONS

1. Using the recorded *voltage-versus-time* graph, correlate the sign and the magnitude of the induced voltage with the movement of the magnet relative to the coil and use Faraday's law to explain the correlation.

2. How can you increase the magnitude of the induced voltage in the coil?

3. In terms of inducing voltage, is there a difference between experiments I(A) and I(B)?

PART II

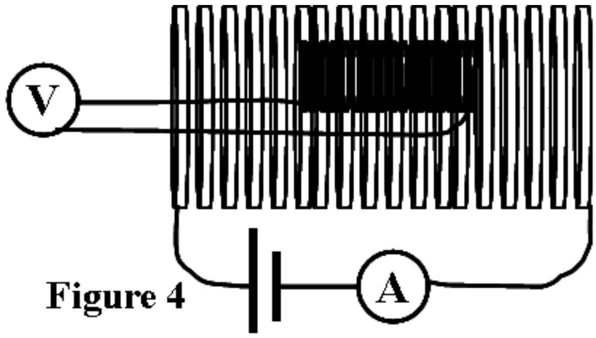

Figure 4

In part II, we use a setup in Figure 4, specifically, Solenoid 2 is placed inside a bigger current-carrying solenoid (Solenoid 1). We measure the induced voltage in Solenoid 2 and quantitatively measure the relation between the induced voltage and the change rate of the magnetic flux through Solenoid 2. The current in Solenoid 1 creates magnetic field inside itself and thus also inside solenoid 2. Changing the current in Solenoid 1 proportionally changes the magnetic field. It thus changes the magnetic flux through Solenoid 2 and subsequently induces a voltage over Solenoid 2.

The magnetic field inside Solenoid 1 is approximately given by the following equation

$$B = \mu_\gamma \mu_0 n_1 I_1, \tag{2}$$

where n_1 is the number of wire turns per unit length for Solenoid 1, I_1 is the current in Solenoid 1, μ_r is the relative permeability for the core material inside Solenoid 2, and μ_0 is the permeability in vacuum. If Solenoid 2 is placed in air, we can use $\mu_r \approx 1$. Thus,

$$B = \mu_0 n_1 I_1. \tag{3}$$

When the current through Solenoid 1 is driven by an *AC* voltage, I_1 is described by

$$I_1(t) = I_0 \sin(\omega t), \tag{4}$$

where I_0 is the amplitude and ω is the angular frequency.

The induced voltage in Solenoid 2 can be derived using Faraday's law and is given as

$$V_2(t) = -\mu_0 N_2 A_2 n_1 \omega I_0 \cos(\omega t), \tag{5}$$

where A_2 is the cross sectional area of solenoid 2 and N_2 is the total number of turns of the wire in Solenoid 2.

(A) Phase difference between the induced voltage and the driven current

Inspecting Equations (4) and (5), it follows that the current in Solenoid 1, $I_1(t)$, and the induced voltage in Solenoid 2, $V_2(t)$, are out of phase. The phase difference can be measured by displaying $I_1(t)$ and $V_2(t)$ using *Scope display*.

Oscilloscope is a standard electric instrument. It can display "real-time" graphs of voltage-versus-time or voltage-versus-voltage (in "X-Y" mode). The vertical and horizontal axes of an oscilloscope can be rescaled independently while displaying data. Once triggered, an oscilloscope can continuously update the measurement by constantly refreshing graphs. Owing to its working mechanism based on deflecting electrons by voltage, an oscilloscope displays only voltage. *Scope Display* in ***Data studio*** is program that emulates oscilloscope and can simultaneously display up to three "real-time" traces.

PROCEDURES

1. Connect Solenoid 1 to Output Channel of ***7500 Interface*** and also to a current sensor via Channel A. Connect Solenoid 2 a voltage sensor via Channel B.
2. In ***Data Studio***, select *Current Sensor* for *Input Channel A* and *Voltage sensor* for *Channel B*. Set appropriate sensitivities for both sensors.
3. Select *Scope Display* from the display window. First select *Channel A* ($I_1(t)$) and then *Channel B* ($V_2(t)$) for display. Even though both channels read voltage, what the first channel reads is the current through Solenoid 1. For each channel, in order to display the trace clearly the vertical scale should be adjusted appropriately. For the horizontal-axis (time), first select *20 ms/div*. You may change the horizontal scale as needed. Set the trigger level of the scope to *0 V*.
4. Open *Signal Generator* from the output window. Select *sinusoidal wave*, set the amplitude to *4.0 V* and the frequency f to *50 Hz (Note:* $\omega = 2\pi f$*)*. Select the auto setting.
5. Click on the *start Button* to start measurement. After the recorded traces of $I_1(t)$ and $V_2(t)$ are satisfactory, print out the graph. Write down all the necessary information on the printed graph. Compare the two traces and obtain the phase difference between $I_1(t)$ and $V_2(t)$.

QUESTIONS

1. The measured phase difference =

2. Does the obtained phase difference agree with the theoretical phase difference shown in Equations (4) and (5)? Explain the possible causes for any discrepancy.

3. Can the two-coil system be considered as a transformer? Why?

4. Is it a step-down or step-up transformer? Explain why you think so.

(B) Induced voltage versus the frequency

In Part II (B), we investigate the linear proportionality between the amplitude of $V_2(t)$ and the modulation frequency ($\omega = 2\pi f$).

PROCEDURES

Repeat steps 1-6 in Part II (A) for the *AC* output with $f = 100, 75, 50, 25,$ and $10\ Hz$. For each frequency, you need to appropriately adjust the vertical and horizontal scales. Using the smart tool to determine the amplitude of $V_2(t)$ and record in Table 1.

TABLE 1

Frequency f (Hz)	Amplitude of $V_2(t)$
100	
75	
50	
25	
10	

QUESTIONS

1. Based on Table 1, discuss whether the amplitude of $V_2(t)$ is linearly proportional to f.

2. Use Excel to calculate the ratio between ω and the amplitude of $V_2(t)$. Show your derivation.

(C) Induced voltage versus the number-of-turns

In Part II (C), we investigate the relation between the induced voltage and the number of turns of the wire in Solenoid 2.

PROCEDURES

1. Follow steps 1-6 as in Part II (A) and set *f* at *50 Hz*.
2. Measure $V_2(t)$ for four different cases when the full length, 3/4, 1/2, and 1/4 of Solenoid 2 is placed inside Solenoid 1. Record the amplitude of $V_2(t)$ in Table 2.

TABLE 2

The length fraction of Solenoid 2 placed inside Solenoid 1	The amplitude of $V_2(t)$
1	
3/4	
1/2	
1/4	

QUESTIONS

1. Analyze the four sets of data and discuss whether the amplitude of $V_2(t)$ is linearly proportional to the corresponding length of Solenoid 2 that is placed inside the magnetic field.

(D) Induced voltage versus the permeability

In Part II (C), we investigate the effect of inserting the supplied iron bar inside Solenoid 2. The permeability of the metal bar is different from the permeability of the air. Assuming μ_r as the relative permeability for the iron bar, Equation (3) becomes $B = \mu_r \mu_0 n_1 I_1$ and Equation (5) becomes $V_2(t) = -\mu_r \mu_0 N_2 A_2 n_1 \omega I_0 \cos(\omega t)$.

PROCEDURES

Set the *AC* output at *50 Hz* and repeat steps 1-6 as in Part II (A). Measure the $V_2(t)$ traces with and without the metal bar inserted inside Solenoid 2.

QUESTIONS

1. Does $V_2(t)$ increase or decrease when the metal bar is inserted inside Solenoid 2? Use Equation (2) to discuss the reason for your observation.

2. Derive the relative permeability of the iron bar inserted in Solenoid 2.

3. Based on your observations, explain why we use strongly magnetic materials as the core for the electrical transformer.