

The University of Hong Kong
Department of Physics

Experimental Physics Laboratory
PHYS3450 Electromagnetism
Experiment No. 3450-2: Faraday's Law of Induction

Demonstrator:

University number:

Objective:

To demonstrate various properties of Faraday's Law such as:

1. Verify the law.
2. Demonstrate the lightly damped oscillation of the hall probe as a simple pendulum.
3. Find the amount of energy lost due to lightly damped oscillation.

Introduction

Electromagnetic induction was discovered independently by Michael Faraday in 1831 and Joseph Henry in 1832. Faraday firstly published the result of his experiment. He explained electromagnetic induction using a concept he called line force. However, this idea was widely rejected at that time, mainly because it lacked mathematical formulation. James Clerk Maxwell grabbed this opportunity and used Faraday's idea as the basis of his quantitative electromagnetic theory.

A voltage is induced in a coil swinging through a magnetic field. Faraday's Law and Lenz' Law are examined and the energy dissipated in a load resistor is compared to the loss of amplitude of the coil pendulum.

A rigid pendulum with coil at its end swings through a horseshoe magnet. A resistive load is connected across the coil and the induced voltage is recorded using a Voltage Sensor and the angle is measured with a Rotary Motion Sensor that also acts as a pivot for the pendulum. The induced voltage is plotted versus time and angle. The power dissipated in the resistor is calculated from the voltage and the energy converted to thermal energy is determined by finding the area under the power versus time curve. This energy is compared to the loss of potential energy determined from the amplitude of the pendulum.

Faraday's Law is used to estimate the magnetic field of the magnet from the maximum induced voltage. Also, the direction of the induced voltage as the coil enters and leaves the magnetic field is examined and analyzed using Lenz' Law.

Theory

According to Faraday's Law of Induction, a changing magnetic flux through a coil induces an emf given by

$$E = -N \frac{dF}{dt} \quad (1)$$

where $F = \int \vec{B} \times d\vec{A} = BA$ for a magnetic field (B) which is constant over the area (A) and perpendicular to the area. N is the number of turns of wire in the coil. For this experiment, the area of the coil is constant and as the coil passes into or out of the magnetic field, there is an average emf given by

$$E = -NA \frac{DB}{Dt} . \quad (2)$$

Apparatus

- 1 × PASCO Scientific EM-8099 Induction Wand
- 1 × PASCO Scientific EM-8641 Variable Gap Lab Magnet
- 1 × PASCO Scientific CI-6503 Voltage Sensor
- 1 × PASCO Scientific CI-6520A Magnetic Field Sensor
- 1 × PASCO Scientific CI-6538 Rotary Motion Sensor
- 1 × PASCO Scientific USB interface
- PASCO DataStudio computer interface
- 1 × large rod stand
- Miscellaneous wirings

Part I: Induced emf

SET UP

1. *Put* a rod in the stand and clamp the cross-rod to it as shown in Figure 1. *Put* the Rotary Motion Sensor at the end of the cross-rod.
2. *Attach* the coil wand to the Rotary Motion Sensor with the tabs on the 3-step pulley just to the sides of the wand as shown in Figure 2.
3. *Put* the pole plates on the magnet as shown in Figure 3. (**Caution: Hold the plates tight and approach slowly to the strong magnet; be careful of the plates' edges and watch out your fingers**).
4. *Adjust* the gap between the magnet poles so the coil wand will be able to pass through but put the magnet poles as close together as possible.



Figure 1: Rod Stand

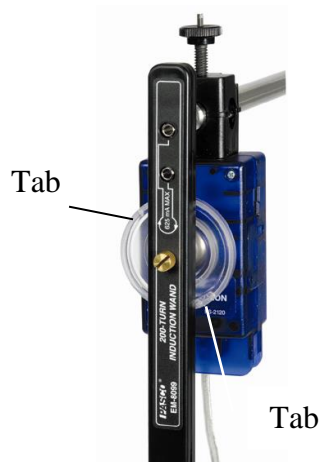


Figure 2: Tabs

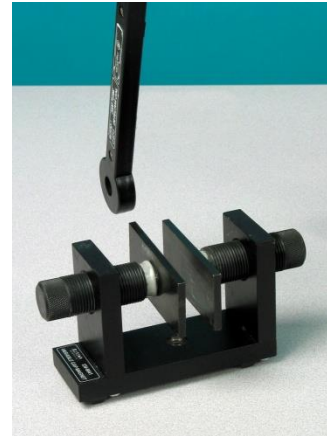


Figure 3: Magnet Pole Plates

4. *Adjust* the height of the coil so it is in the middle of the magnet. *Align* the wand from side-to-side so it will swing through the magnet without hitting it.
5. *Plug* the Voltage Sensor into a USB Link or similar PASPORT interface. Connect the interface into the computer. Repeat for the Rotary Motion Sensor and the Magnetic Field Sensor.
6. Plug the Voltage Sensor banana plugs into the banana jacks on the end of the coil wand. Drape the Voltage Sensor wires over the rods as shown in Figure 1 so the wires will not exert a torque on the coil as it swings. It helps to hold the wires up while recording data.
7. Open the DataStudio file called "InducedEMFpas.ds"

PROCEDURE

1. Click 'START'. With the pole plates on the magnet, use the Magnetic Field Sensor to measure the magnetic field strength between the magnet poles. Click STOP'.
2. Click 'START' and pull the coil wand back and let it swing through the magnet. Then click 'STOP'.
3. Use the Magnifier Tool to enlarge the portion of the voltage vs. time graph where the coil passed through the magnet.
4. Use the mouse to highlight the first peak and find the average voltage.
5. Use the Smart Cursor to determine the difference in time from the beginning to the end of the first peak.

ANALYSIS

1. Calculate the value of the average emf using Equation (2). Compare this value to the value measured from the graph.
2. Identify on the graph where the coil is entering the magnet and where the coil is leaving the magnet.



Figure 4: Coil Passes through Magnet

3. Is the emf of the first peak positive or negative? Taking into account the direction the wire is wrapped around the coil, does the sign of the emf correspond to the direction expected using Lenz's Law?
4. Why is the sign of the emf of the second peak opposite to the sign of the first peak?
5. Why is the emf zero when the coil is passing through the exact center of the magnet?

Part II: Energy

THEORY

If the center of mass of the pendulum starts from rest at an initial height h_i , its potential energy is

$$U = mgh_i. \quad (3)$$

As the pendulum swings and passes through the magnet, some energy is lost to mechanical frictional heat and some energy is converted to electrical energy and then to thermal energy in the resistor. Thus the center of mass of the pendulum does not rise to the same height but rather to a lower final height, h_f . See Figure 5. The total energy lost by the pendulum is equal to its change in potential energy:

$$TotalEnergyLost = \Delta U = mg(h_f - h_i) \quad (4)$$

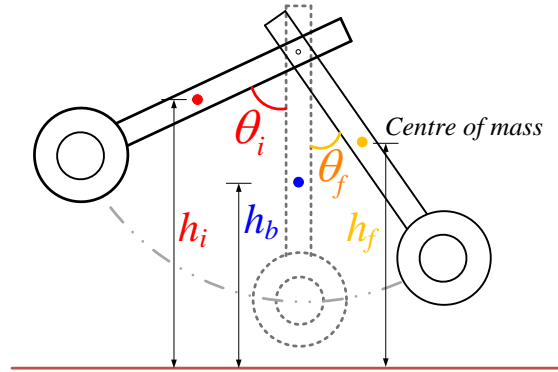


Figure 5: Coil Height Decreases

$$E = \int P dt = \text{Area Under } P \text{ vs. } T \text{ graph} \tag{5}$$

where P is the power and t is time.

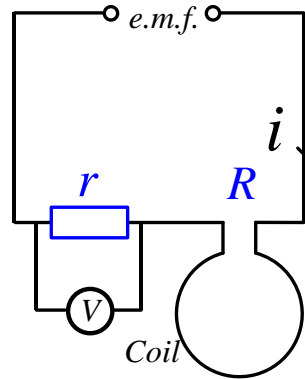


Figure 6: Coil and Resistor Circuit

The power is given by

$$P = I^2 (R + r) = \frac{V^2}{R + r} \tag{6}$$

where V is the voltage across the resistor (r), I is the current through the coil, and R is the resistance of the coil. See Figure 6. In this experiment, $R = 1.9 \Omega$ and $r = 4.7 \Omega$.

PROCEDURE

1. Remove the coil wand and plug in the 4.7Ω resistor to the end of the wand handle. Find the coil wands center of mass by balancing it on the edge of a table. Measure the distance from the pivot point to the center of mass.
2. Remove the magnet pole plates. Attach the coil wand to the Rotary Motion Sensor and plug in the Voltage Sensor as shown in Figure 7.
3. Open the DataStudio file called "InductionEnergyPAS".
4. First, the amount of energy lost to friction will be measured by letting the pendulum swing without the coil connected in a complete circuit. Pull the resistor plug out and plug it back in with one of its plugs out to the side and one plug in the wand (see Figure 8). This will disconnect the coil while not changing the center of mass or disconnecting the Voltage Sensor wires.



Figure 7: Coil and Resistor

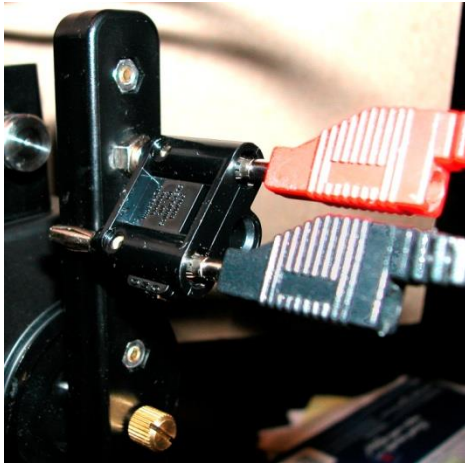


Figure 8: Resistor Disconnected

5. Click START with the coil at rest in its equilibrium position between the coils. Then rotate the wand to an initial angle of 25 degrees and let it go. Click STOP after it has swung to the other side.
6. Measure the angle to which the pendulum rises after it passes once through the magnet.

Calculate the initial and final heights using the distance from the center of mass to the pivot and the initial and final angles. Calculate the energy lost to friction using Equation (4).

7. Reconnect the resistor with both plugs in the wand. This completes the series circuit of the resistor and coil.
8. Click START with the coil at rest in its equilibrium position between the coils. Then rotate the wand to an initial angle of 25 degrees and let it go. Click STOP after it has swung to the other side.
9. Measure the angle to which the pendulum rises after it passes once through the magnet. Calculate the initial and final heights using the distance from the center of mass to the pivot and the initial and final angles. Calculate the total energy lost using Equation (4).
10. Highlight both peaks on the power vs. time graph and find the area. This area is the energy dissipated by the resistor.
11. Add the energy dissipated by the resistor and the energy lost to friction. Compare this to the total energy lost by the pendulum.

References:

1. Pasco Scientific Instruction Manual for Faraday's Law PASPORT Experiment File
2. Hyperphysics - <http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw.html>
3. Maxwell, James Clerk (1904), *A Treatise on electricity and Magnetism*, Vol. II, Third Edition. Oxford University Press.

(revised August 2017)