EC-5 MAGNETIC INDUCTION

If an object is placed in a changing magnetic field, or if an object is moving in a non-uniform magnetic field in such a way that it experiences a changing magnetic field, a voltage will be induced in the object that is proportional to the rate of change of the amount of magnetic flux passing through the object. This is Faraday's law.

If the object is a conductor, a current will flow. The sign of the voltage will be such that, if a current flows, it will generate a field that will *oppose the change* in the magnetic field, or the experienced change in the magnetic field, that induced the voltage. This is Lenz's law. It's the reason for the minus sign in the equation that describes Faraday's law.

The induced voltage, and any current it produces, will last only as long as the external field is changing or is felt to be changing. For example, if we have a loop of wire, and we turn on a magnetic field that passes through it, a current will flow in the loop that will generate a field inside the loop opposite to the field we are turning on. The current will flow only as long as it takes to turn on the external field. (Why? Once the field is fully turned on, is it still changing?)

Alternatively, if we move a loop from a region of zero magnetic field into a region of uniform field, the induced voltage will produce a current which generates a field inside the object that’s opposed to the one into which we are moving the object, because an opposing field opposes the change. However, this is not always so. *Sometimes a field in the same direction as the external field is the one that will oppose a change*. See below.

Once the loop is in a uniform field, we may continue to move it through the field without inducing a voltage, because, since the field is uniform, the loop is no longer experiencing a changing field. But if we rotate the loop, it will experience a changing field even while fully inside a uniform field, because it will experience a change in the direction of the field.

If we move a loop from a region of uniform field into a region of zero field, a current will be produced which generates a field in the object that’s in the same direction of the uniform field, because in that case, *a field in the same direction opposes the change*.

Likewise, if a loop has a magnetic field passing through it, and we turn off the field, a current will flow which will generate a field in the same direction as the one we are turning off, opposing the change.

For any of the effects described above to be apparent, there must be a component of magnetic field perpendicular to some part of the object. If a loop were extremely flat or thin, and the plane of the loop were parallel to the field, we could move the loop in or out, or turn the field off or on, without changing the field passing through the loop. Off or on, there would be no field *passing through* the loop. It would always be parallel to the plane of the loop.

Of course, any real object is three dimensional, so there will always be parts of the object that are perpendicular to a field, and in the above situations currents will always flow. But if the parts of the object that are perpendicular to the field are very small, then the currents and the field they generate will also be very small.

If a current flows in any ordinary conductor, there will be electrical power associated with it that will heat up the conductor. The heat energy must be coming from somewhere; it has to come from the work done in moving the object. Thus in order to move it so that it feels a changing magnetic field, we will have to apply a force. We will feel some resistance as we move the object. The notion that there is a natural resistance to a change in magnetic field is not just an equation or some words on a page. It's something we can actually feel.

OBJECTIVES

After completing this lab, you should be able to:

- Predict the direction of an induced current if you know the magnetic fields, how they are changing, and the geometry of the situation.
- Predict the induced voltage in a coil and the shape of its voltage vs. time graph if you know the shape of the graph of the inducing magnetic field vs. time.

PREPARATION

Read the material in your textbook on magnetic induction, Faraday’s law, Lenz’s law, inductance and circuits with inductors and resistors in them.

Before coming to lab, you should be able to:

- Understand the concept of magnetic flux and how it relates to magnetic fields and magnetic field lines.
- Write down the equation that describes Faraday’s law and understand the meaning of all the quantities involved.
- State Lenz’s law and understand its meaning.
- Write the equation that defines inductance and understand the meaning of all the quantities involved.
- Write the equation for the inductance of a solenoid in terms of its dimensions and number of turns and understand the meaning of all the quantities involved.
- Write the equation for the time constant of a circuit containing an inductor in series with a resistor and understand the meaning of all the quantities involved.

PROBLEM EC-5a: MAGNETIC FORCES ON MOVING OBJECTS

You are working as a consultant to a manufacturer of vending machines. The chief design engineer wants some help testing a new idea. She thinks that a transverse magnetic field will slow down a rolling coin after it has been dropped into a coin machine. She further believes that the amount of "slowdown" will depend on the size and shape of the coin.

?	If a moving object passes through a transverse magnetic field, will it experience a force opposing its motion? Will the magnitude of the force opposing the motion depend on the size and shape of the object?

EQUIPMENT

In order to test this idea, you have had a number of aluminum pendulums made with different sized and shaped ends. You have a strong magnet set up so that the pendulums can swing through a gap between the poles. You also have a couple of smaller magnets, with their poles labeled, that you can use to find out which pole of the strong magnet is which. **Hold the smaller magnets very gently, and don't push them close to the strong magnet. Let them pull you. The strong magnet is so powerful that it can actually reverse the magnetization of the smaller ones.**

PREDICTION

Based on Fig. 1, rank the pendulums in order of the amount of force that will oppose their passage through the magnet gap. (Recall that “slowdown” is negative acceleration, which is proportional to opposing force.)

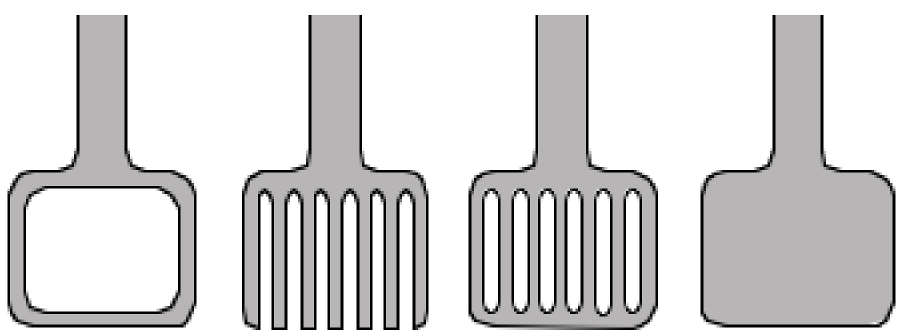


Fig. 1 Four pendulums

METHOD QUESTIONS

1. Based on the shape of the pendulums, which one will have the least ability to form current loops that can generate fields opposing the changes in the field the pendulums experience as they swing through the magnet gap?
2. Which ones will have the most ability to form such current loops? Which are in between, and in what order?
3. If some pendulums have more (or less) current generated as they swing through the gap, which ones will generate more heat as they pass through? The ones with more current or the ones with less?
4. Where does the heat energy come from? What kind of energy is turning into heat energy? What does that mean for the motion of the pendulum?

Now make your predictions.

EXPLORATION

How can you measure how quickly each pendulum slows down? How do you know what differences in the rates of slowing down would exist even without a magnetic field? How can you measure that?

How can you check (using only things that are supplied in the equipment above, or are already in the lab) to make sure that someone in a previous class has not already reversed the magnetization of one of the smaller magnets? (Hint: how does a compass work?)

How can you use one of the smaller magnets with known poles to find out which pole of the large magnet is which, so that you will know what direction the magnetic field in the gap is pointing?

Develop a measurement plan and write it down.

MEASUREMENT

Carry out your measurement plan. Record your results. In addition to actually measuring the slowdowns, *each member of the team should try pushing the different pendulums through the gap and actually feeling the different degrees of resistance*.

Since there is only one pendulum setup per lab, your team may have to wait until there is a free moment while working on another problem.

ANALYSIS

Do your results match your prediction? Why or why not?

For the pendulum that's a single loop, draw a diagram that shows the direction of the magnetic field in the gap, and which way the induced current flows when the pendulum is swinging into the gap. Explain why you chose the direction for the current that you have indicated in your drawing.

Do the same for the pendulum swinging out of the gap.

CONCLUSION

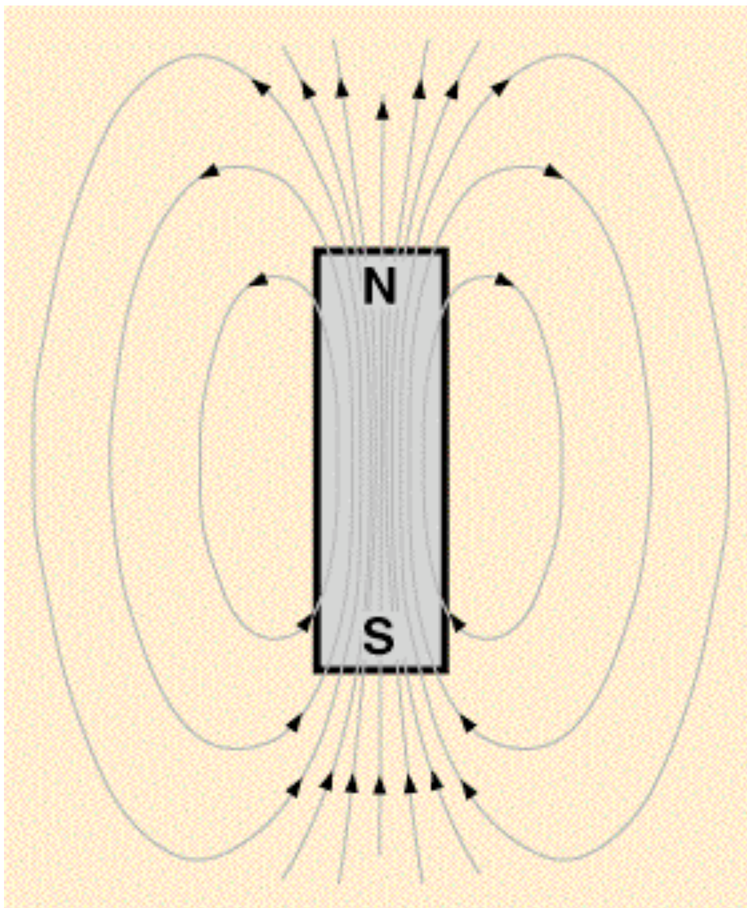
Will the chief engineer's idea work? Explain how, and what factors will affect the rate the coins slow down as they roll through the magnet.

FURTHER QUESTIONS

Suppose you had some coins that were made of a conductor that had, say three or four times the resistivity of the metal in ordinary coins. If they rolled at the same speed, would the same voltage be induced in them as they passed through the magnet? Would the same current be induced? Would it generate as much heat? Would you predict that they would slow down as much as the metal coins? Why or why not?

PROBLEM EC-5b: IF A MAGNET FALLS THROUGH A COIL OF COPPER WIRE, IS THERE AN INDUCED VOLTAGE IN THE COIL?

The magnetic field lines surrounding a typical bar magnet are shown in the picture below:



The rule we will investigate is called Lenz's Law. In order to understand Lenz's Law, you have to know:

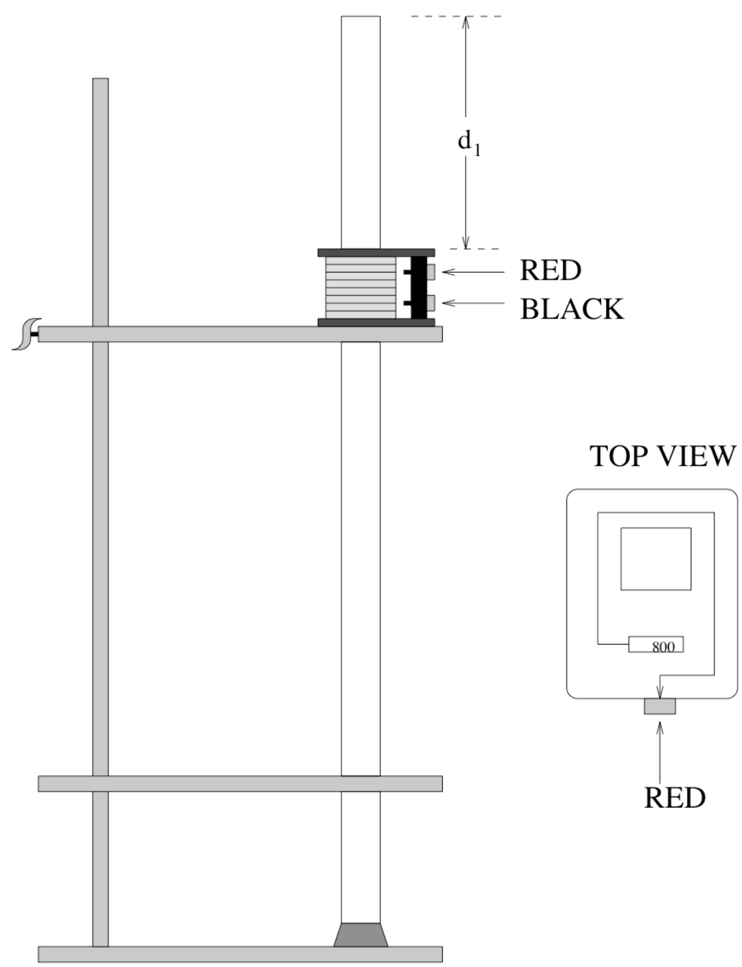
--a current flowing through a wire generates a magnetic field. The direction of the magnetic field may be remember by the "right-hand rule" (Section 19.6).

--if the magnetic flux through a conducting loop changes, a current will be induced in the loop (this is an example of Faraday's Law, Section 20.2).

Lenz's law determines the direction of the current that the changing magnetic flux induces in the loop: the current will go in a direction such that the magnetic field it generates opposes the change of the (externally generated) magnetic flux.

EQUIPMENT

Your test apparatus is a 400-turn coil labeled according to its winding direction, mounted on an adjustable stand so that a bar magnet can be dropped through it from different distances above it. There is a rubber stopper to cushion the landing of the bar magnet, and a plastic tube to keep it from falling on the floor. **The bar magnet is brittle and is likely to break if it falls on the floor, so you must be careful with it. *Hold onto the plastic tube* when dropping the magnet through the coil, so that the magnet cannot bounce out onto the floor.**



Adjustable stand, showing 400-turn coil

In addition to this apparatus you will have a “voltage sensor” (Pasco's fancy name for a dual banana cable) and the Pasco interface, with which to display a graph of the induced voltage on the computer screen.

METHOD QUESTIONS

To help you in your prediction, think of an induced voltage as the coil temporarily becoming a battery. Be careful, though, because the current inside a battery doesn't flow from positive to negative like it does in an external circuit the battery is connected to. A battery acts as a "charge pump" that pushes its internal charge from the negative terminal to the positive terminal. The current inside a battery flows from *negative to positive,* the *opposite* of what the battery makes it do in an external circuit.

1. If you drop the magnet north pole first through the coil, what is the direction of field lines entering the coil?
2. What is the direction of the field the coil will try to generate in order to oppose the change?
3. Looking down at the top of the coil, you see from the labeled winding direction that current *leaving* the red terminal has to flow *clockwise* around the coil. Using the right hand rule, which way would the field generated by a clockwise current point?
4. Is this the kind of field needed in question 2? As the north pole of the bar magnet approaches, causing a change in the magnetic field inside the coil, which way will the current flow in order to generate a field *opposing* the change?
5. If the coil has to become a battery to make the current flow this way, which terminal of the coil, red or black, will become positive? Think of the Pasco interface as a resistor and the coil as a battery pushing the current through the resistor.
6. Let's assume you have plugged the red wire of the voltage sensor into the red terminal on the coil and the black wire into the black terminal. If the red terminal becomes positive, the graph of the voltage will be positive; if the red terminal becomes negative, the graph be negative. Will the graph be positive or negative when the north pole is approaching the coil? How do you know (from magnitude of the induced voltage) when the field is increasing fastest?
7. Assuming that the field is strongest right at the end of the magnet, when will the magnitude of the induced voltage be the greatest?
8. What happens to the magnetic flux through the coil as the north pole begins to slide out the bottom of the coil? How will the induced voltage reflect that?
9. What will the induced voltage be as the central part of the magnet slides through the coil? Will the flux through the coil be changing then? Assume that the field is weak along the sides of the magnet, and strong at the ends.
10. Ask yourself questions 1-9 about what will happen as the south pole enters the top of the coil, slides through the middle and leaves at the bottom. Draw the voltage graph you expect to see for the entire process.

11. Using kinematics, if you know how high above the coil you drop the magnet, can you estimate the speed of the north pole as it passes the center of the coil? What about the speed of the south pole as it passes the center? (Will it be going the same speed as the north pole? What happens to any object in free fall?) How will the graph reflect the relative speeds?
12. How would the graph change if magnet fell farther before it entered the coil?
13. How would the graph change if the magnet were reversed and fell south pole first?

EXPLORATION

Here are some instructions for how to set up the PASCO software:

How to get the computer ready to take data:

How to turn on the computer and start DataStudio:

--Connect sensor to interface (yellow plug in leftmost input, black in next input).

--Turn on power strip

--Turn on power to Pasco Interface (black box on table)

--Turn on computer

--Turn on monitor

--Click "**Student**" when computer boots up

--Double-click "**DataStudio**" icon on desktop

--Click "**Create Experiment**". "Experiment Setup" box, showing picture of Pasco interface, should appear.

--Take one of the red-and-black conductors and connect it to the coil mounted on the tall stand with the red base. Connect the other end to the "A" slot on the PASCO interface. Set the coil about nine inches above the base.

--Click on the "A" sensor. Scroll down to "Voltage Sensor". Select and add it.

--Double-click "Graph" on the lower left-hand side. A graph should pop up.

--Take the magnet out of the tube. Replace the rubber stopper at the bottom.

--Before you run anything, a word of caution about the magnet: it is **very** brittle, and can break easily. We are going to be dropping it repeatedly, so you must take care to **always** hold the bottom of the tube/stopper tightly when dropping the magnet.

--Change "Sample Rate" to 1000 Hz.

--Click "Start".

--Making sure to hold the bottom of the tube, drop the magnet in the tube.

--Click "stop". You have just taken your first data set!

Use the magnifying glass icon (the fourth from left) to blow up the "spiky" part of the curve you just recorded.

The graph you see is the voltage induced in the copper coil.

- Why do the two peaks have different heights?
- Why are the two peaks in different directions?
- Why is the second peak taller than the first?

Repeat the above procedure, with the coil set at medium height (a little higher than it was). Then do it again with the coil as high as you can get it on the stand.

Answer the above questions for all three heights.

Print or sketch the graphs for your journal.

Now turn the magnet upside down and repeat the above procedure.

Make sure everyone on the team gets to operate the computer and drop the magnet through the tube at least once.

You should see that as the coil gets higher, the heights of the two peaks decrease. Why is this?

Is it true, that for every height, the second peak is taller?

Can you check the bar magnet to see if the pole labeled N is really the north pole? (Be careful not to drop it!) What difference would it make in your results if the poles were not correctly labeled?

ANALYSIS

Do your graphs look different than you predicted? How are they different and what do you think makes them different?

Consider each part of a graph, as you did in the method questions, and explain why it looks the way it does.

Consider how the graphs changed when the magnet fell further before entering the coil, and when the magnet fell south pole first vs. north pole first. Explain the changes.

Look at some of the other teams' graphs. Are some of the details different? Why? Note particularly the shape of the graph in the center between the two peaks.

Could you tell the difference between a magnet that had a stronger magnetization and one that came off the line faster?

PROBLEM EC-5d: FARADAY'S LAW AND INDUCTANCE

?	Can you create a magnetic field that will vary according to a variety of voltage waveforms? If you use a changing voltage to create a magnetic field, and let the field induce a voltage, will the induced voltage be proportional to the slope of the changing voltage waveform?

EQUIPMENT

You will have the Pasco interface, which has an oscilloscope (a device which can visually display a voltage *vs*. time graph, *i.e*. a voltage waveform, and a signal generator that can generate several different voltage waveforms. You will also have two voltage sensors, so you can simultaneously display two waveforms on the oscilloscope, and a power amplifier that can take a voltage waveform and use it to drive current through a circuit. You will use it to drive a current through a solenoid. The solenoid is a coil of about 2600 turns of wire on a plastic cylinder about 2.8 cm in diameter and 11 cm long, having a resistance of around 82Ω.

For reasons that will become clear later, you will need a 100Ω resistor in series with the solenoid. A second solenoid will fit inside the first; the magnetic field from the first solenoid will induce a voltage in the second. An iron rod will fit inside the second solenoid. Since iron attracts and strengthens magnetic fields, presence of the iron will strengthen the magnetic field and ensure that nearly all of the field lines from the outer solenoid also pass through the inner one.

PREDICTION

Will a graph of the magnetic field from the outer coil look the same as the graph of the voltage from the signal generator? Will the voltage induced in the inner coil be the slopes of the magnetic field graph?

METHOD QUESTIONS

1. Recall that a solenoid—a coil of wire—besides resistance, also has inductance. If you know the number of turns and the dimensions of the solenoid, can you calculate its inductance? Stronger magnetic fields, changing at the same rate, induce larger voltages. Iron strengthens magnetic fields, so what effect will the iron core have on the inductance of the solenoid? (See your textbook for relations between inductance, current, induced voltage, and magnetic flux.)

2. This circuit has an inductance L (the solenoid) in series with a resistance R (the wire in the solenoid + the resistor). What is the approximate time required to start a current flowing through inductor in a series LR circuit like this one? What do you expect the iron do to the time required?

3. The current in the coil produces a magnetic field. What is the approximate startup time for the magnetic field? If the voltage changes in a shorter time,

will the current in the solenoid be able change as fast? Since the current generates the field, will the field be able to change as fast as the voltage?

4. A square wave keeps the same *magnitude* of voltage, but reverses the *sign* of the voltage almost instantly at regular intervals. Between reversals, the voltage is constant. What does the graph of a square wave look like? Draw it. What would the slope of the square wave be at the points where the reversal takes place? What about the slope in between reversals?

5. If you connect a square wave voltage across the coil, will the current in the coil be a square wave, too? What do you think the graph of the current will be? Below your graph of the square wave voltage, draw the graph of the current in the coil, keeping in mind that the current will take one or two inductive time constants to catch up with each change in the voltage. Below the current graph, draw the graph of the *slope* of the current waveform. The voltage reverses twice for each period of the square wave, and shorter periods mean higher frequencies (recall the relation between frequency f and period T). If the frequency of the square wave is high enough, the current and therefore the field will not be able to keep up with it (see question 3). What will happen to the graph of the current and the graph of its slope as the frequency is increased? Note that if τ is the inductive time constant of the circuit, $f = 1/\tau$ is too high a frequency for the current to keep up! (Why?)

6. Instead of instantly reversing like a square wave, a sawtooth wave zigzags back and forth between equal magnitude positive and negative voltages. Starting at the positive voltage, it slopes downward in a straight line and arrives at the negative voltage after a fixed time interval. It then begins a straight-line journey back to the positive voltage in the same length of time. The cycle then repeats. The magnitude of the upward and downward slopes is the same. Instead of the voltage reversing instantly, as in a square wave, the slope reverses instantly. Will the current in the coil be able to keep up with the sawtooth wave voltage any more easily than the square wave? Why or why not? Draw the sawtooth graph, your prediction of the current graph it will produce, and the slope of the current graph.

7. Answer question 6, but for a sine wave voltage.

Now make your predictions.

EXPLORATION

Below please find diagrams of the apparatus you are to set up. They are a bit complicated, so do ask your TA for help if you have trouble.

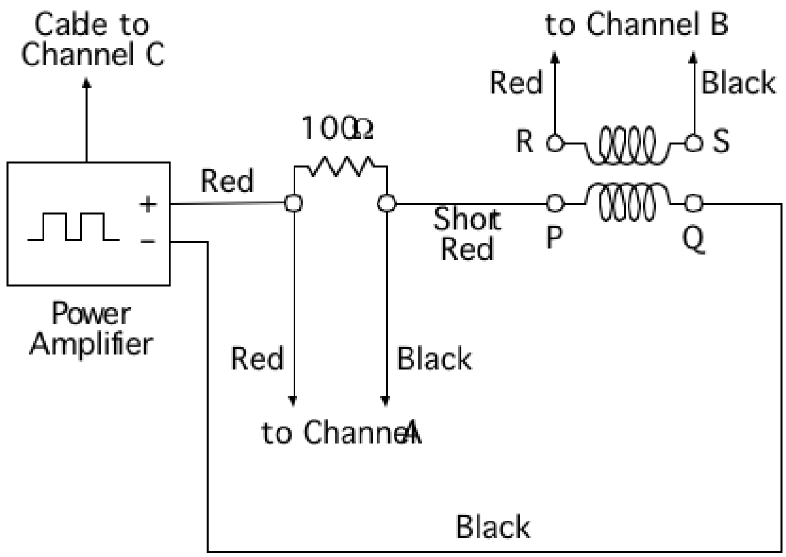


Fig. 2. Diagram showing resistor, coils and Pasco connections.

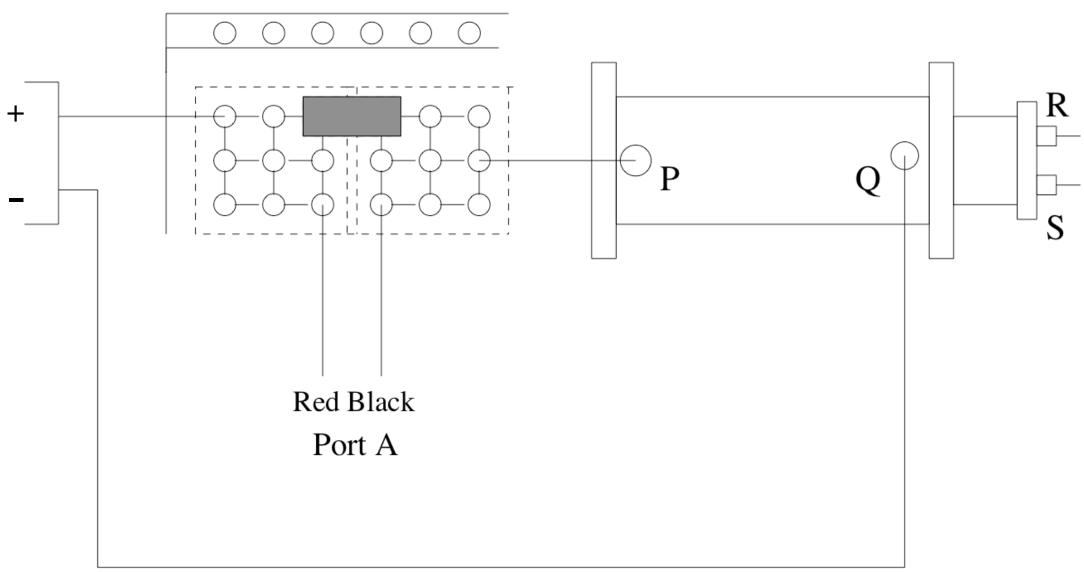


Fig. 3. The physical set-up

Once you have set up the apparatus, turn your attention to setting up the computer. Quit out of DataStudio, and relaunch it (this is easier than trying to modify an old experiment).

--You should have a wire from the positive end of the power amplifier to the resistor, a wire from the resistor to the big coil, and a wire from the big coil to the negative end of the power amplifier.

--You should have one of the red and black cables connected across the resistor. Plug it into input A on the PASCO interface.

--You should have the second red and black cable connected across the small coil (it's sitting inside the big coil). Plug it into input B on the PASCO interface.

--Take the gray cable, connect one end to the back of the power amp, and the other to channel C on the PASCO interface.

--Make sure the power amp is plugged in and turned on.

--Similar to what you did in the last part of this lab, set up Channels A and B as voltage sensors.

--Set up channel C as "Power Amplifier". A small Signal Generator box should appear.

--Click on "Graph". When you are asked to choose a data source, choose Channel A.

--Click on "Voltage, ChB" in the upper left-hand corner, and drag it onto the graph that just appeared.

--Click on the last drop-down menu in the graph window, and uncheck "Data Grouping". The graph should now split into two, with only one dataset on each graph.

--On the signal generator, make sure that "Auto" is set.

--Click "Start", and let it run for 5 or 10 seconds, and then click "Stop". You should see two graphs now.

--Set the y scale on each graph, so that you can actually see the curves (ask your TA for help how to do this, if you need to). About -5 to 5 for the top one, and about -0.02 to 0.02 for the bottom should be about right. If both are changing at the same time, make sure to uncheck "Apply to all".

--If all is well, you should see two curves right now, with the top looking pretty smooth, and the bottom somewhat noisy (which is OK).

- The two curves are out of phase (when one is maximum, the other is zero, and vice-versa). Why is this?
- Why does the output (lower graph) have a much smaller amplitude than the input (upper graph)?

Tip: if one or both of the curves is zero, it may be because one or both of the red and black cables is hooked up backwards. You will measure zero if you either connect the positive output of the power supply to the ground of the PASCO interface, or you connect the positive (red) terminal of one of the measuring cables to the ground (black) terminal of the other.

Try all of this again with a square wave and a triangle wave (change from "Sine Wave" on the Signal Generator). Comment on the shapes of the input and output voltages.

Try different frequencies to see how the current in the solenoid changes with the frequency. As you change the frequency, you may need to adjust the horizontal scale in the Scope window like you did the vertical.

Why must the current in the solenoid be the same as the current in the 100Ω resistor? Why can't we just measure the voltage on the solenoid if we want to know the current through it? Do the voltage and current in the solenoid obey Ohm's Law?

Take a look at the channel B waveform. Make whatever adjustments you need in order to get a good view of the waveform. Does the channel B waveform look like your slope drawing from method question 6? If the polarity is reversed, reverse the leads on the channel B voltage sensor. Once you get satisfactory waveforms you can freeze them on the display by clicking STOP. This will save the display as a recorded data set in the setup window. Print the waveforms for your journal.

Now connect the channel B voltage sensor across the big coil and make another recording. You may have to make some adjustments before clicking STOP, in order to get a good view. What is channel B displaying? If the current in the circuit is the same everywhere, why do the two waveforms look different? Is it because the big coil has both resistance *and* inductance? Or, alternatively, is it because the big coil has both an Ohm's Law voltage *and* an induced voltage from the changing magnetic field?

If you subtract the channel A waveform, due solely to resistance, from the channel B, what's left is the non-resistive voltage, *i.e.* the induced voltage. Draw an approximate graph of what is left over. Does it look like the induced voltage display from your first recording, with channel B connected across the smaller coil? Why or why not? (You may need to reverse the leads to get the polarity correct.) Print the display for your journal.

If you have not already seen what happens when the frequency is too high, gradually increase the frequency of the signal generator beyond the limit of method question 3. What happens to your waveforms? Why?

MEASUREMENT

There is nothing quantitative to measure in this lab. Re-record the displays from your exploration with the sawtooth and sine waves. Then for the square wave again, but without the iron core. With no iron core, has the upper limit of the frequency (for the current to follow the voltage) changed? How has it changed?

Has the amplitude of the induced voltage changed? How has it changed? Why? Re-adjust the channels as necessary while recording, to get a good view. Print the displays for your journal.

Make sure that all lab team members get to participate in setting up the circuit and recording the data.

ANALYSIS

If you have answered all of the exploration and measurement questions for your recordings with and without the iron core, you have already done a big part of the analysis.

Do the induced voltage displays show the slope of the signal generator voltage waveforms? For each type of waveform, how does it differ and why?

Explain the differences between the square wave recordings with and without the iron core. Note and explain not only the change in amplitude of the induced voltage, but also any differences in the shapes of the waveforms with and without the iron.

For the last recording, the square wave *without* the iron core, expand the horizontal scale and use the cursor button in the Scope window to determine how long it takes for the current to reach 63% of its maximum value. From what you know about the time constant in a circuit having an inductance L in series with a resistance R, and what you know about the total resistance in the circuit (What other resistance is in the circuit besides the 100Ω resistor? See the equipment section), can you calculate the inductance of the large coil? Now double-click your first recording of the current waveform, the square wave *with* the iron core, and repeat your calculation. You may have to lower the frequency and change the horizontal scale again. How much change in the inductance occurs due to the iron core?

CONCLUSION

Do your recorded displays look like your drawings from the method questions? Explain any differences.

By now you should have a good grasp of how well your circuit can display a waveform and its slope. What are its limitations and why do they occur? Would they prevent your idea from being used to make good classroom demonstration of the slope of a graph for a calculus class?

FURTHER QUESTIONS

Given that major constituents of electrical power grids are transformers with iron cores, would you recommend changing the sine wave used in power grids to a sawtooth or a square wave? Why or why not?