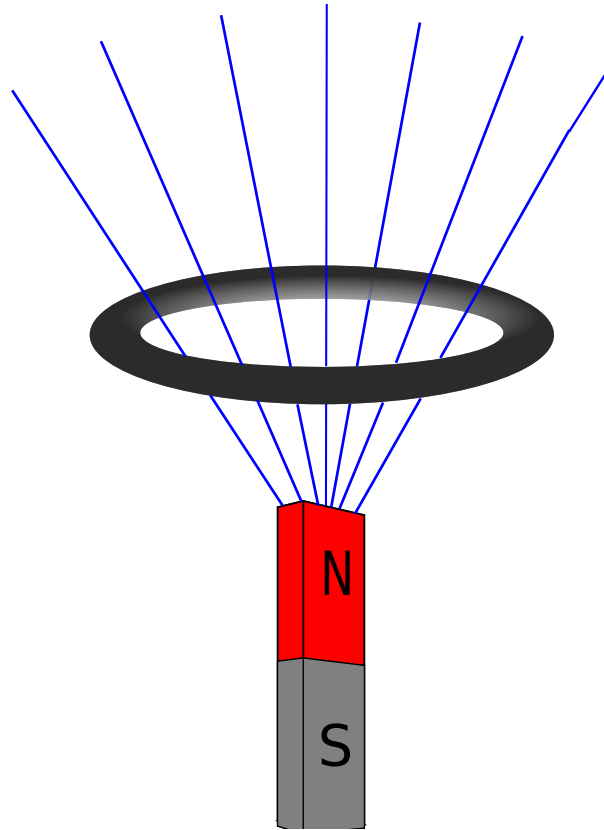


Lab III - Magnetism and induction



Motivation

There is something almost magical about magnetism which has fascinated humans throughout centuries. As children, we are captivated by the ability of magnets to affect metals over distance and this property is one of the reasons which makes magnetism so interesting. Another reason for why magnetism is so interesting, is because of its close link to electricity, as the name electromagnetism suggests. One way to explore this connection is by studying the electromagnetic induction that causes current to flow by changing magnetic fields. In this lab we are going to study this effect, in addition to Lenz's law which shows how electricity and magnetism interact.

In final part of this lab we will study hysteresis curves. These illustrate a material's ability to become magnetized in an external magnetic field and their ability to stay magnetized after the external field is removed.

History

In 1831, the physicist and chemist Michael Faraday tried to find relationship between electricity and magnetism. He made a solenoid by winding copper wire around a cardboard cylinder and connected the two ends of the wire to a galvanometer.¹ He then pushed a bar magnet into the cylinder and saw

¹A galvanometer is an instrument that measures electricity.

that the needle on the galvanometer jumped. When he removed the magnet the needle jumped again in the opposite direction. This was a verification of the connection between magnetism and electricity that showed how a changing magnetic field induces electric current.² Some years later the Russian physicist, Lenz, put a definite direction on the induced currents from the direction of the magnetic field.

1 Faraday's induction law

Faraday's law of electromagnetic induction is one of the most important laws in electromagnetism. Understanding this law is beneficial because so many of our daily life function are built on the principle behind Faraday's law. It predicts how a magnetic field will interact with an electric circuit to produce an electromotive force (emf) and can be stated by the following:

*The induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux through the circuit.*³

1.1 Procedure

1. Start Data Studio on the computer. Select Create Experiment on the first screen.

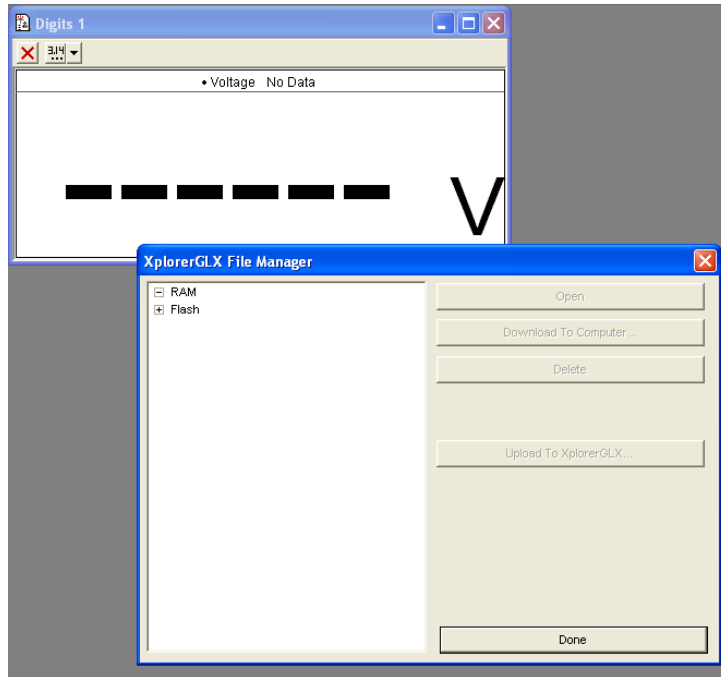


Create Experiment

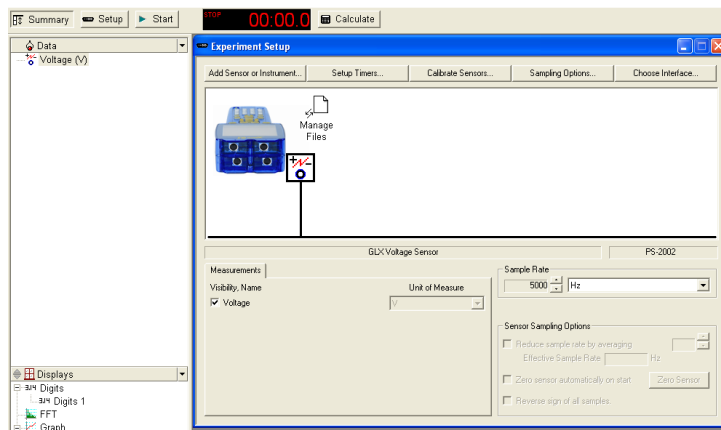
2. Connect the data logger to the power source and to the computer using the USB cable.
3. Connect the solenoid to the data logger using the voltage-port (marked V).
4. You should now see a voltage display. (If you get a window with the title "XplorerGLX File Manager", you may close this by clicking "Done").

²Faraday was actually disappointed over what he just had found, since he was looking for a constant flow of current!

³See Wikipedia, Faraday's law, http://en.wikipedia.org/wiki/Faraday%27s_law_of_induction (as of Oct. 17, 2012, 11:26 GMT+1). Wikipedia cites Sadiku, M. N. O. (2007). Elements of Electromagnetics (fourth ed.). New York (USA)/Oxford (UK): Oxford University Press. p. 386. ISBN 0-19-530048-3.



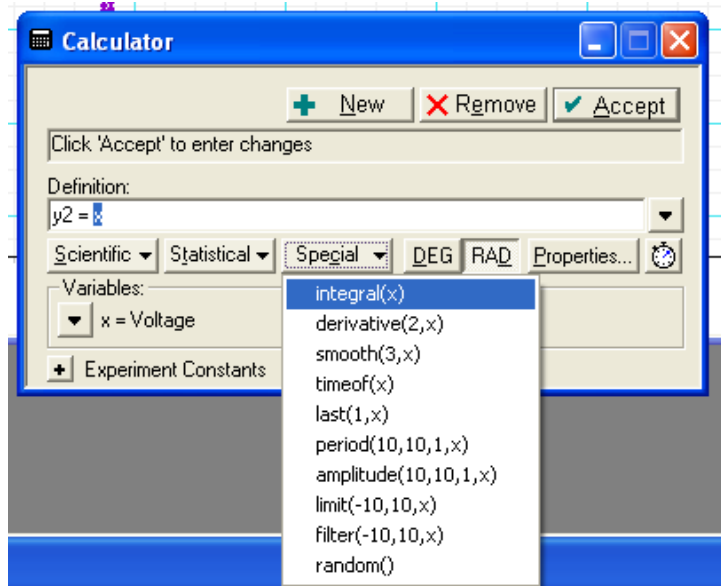
5. Select Voltage in the list to the left, click the Setup-button and change the Sample Rate to 5000 Hz.



6. Click Start to start the data logging.
7. Drop a magnet through the solenoid from about 2 cm above it. Remember to catch it on the other side!
8. Click Stop to stop the data logging.
9. Zoom in on the area of the graph corresponding to the time you dropped the magnet.
10. Print the graph.

We now want to integrate the voltage.

1. Click Display > Calculate.
2. Select Special > Integral



3. Click Accept and close the dialog.
4. Zoom in on the integral and observe its value before and after the magnet was dropped through the solenoid.
5. Print the graph.
6. Repeat the experiment for a larger height, for instance 8 cm above the solenoid (make sure you hit the hole in the solenoid!).
7. Repeat the experiment, but this time drop the magnet the other way (i.e. with the end pole first).

2 Lenz's law and eddy currents

We have seen that a moving magnetic field affects a conductor and induces currents in that conductor. We will now explore how this induced current acts back on the moving magnetic field.

2.1 Theory

Lenz's law is all about conservation of energy, and one way to state this law is as follows:

*An induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux.*⁴

2.2 Procedure

- Take a conductive but non-magnetic tube, and drop a piece of steel down the tube.
- Next, use the same tube, but drop a magnet down the tube.

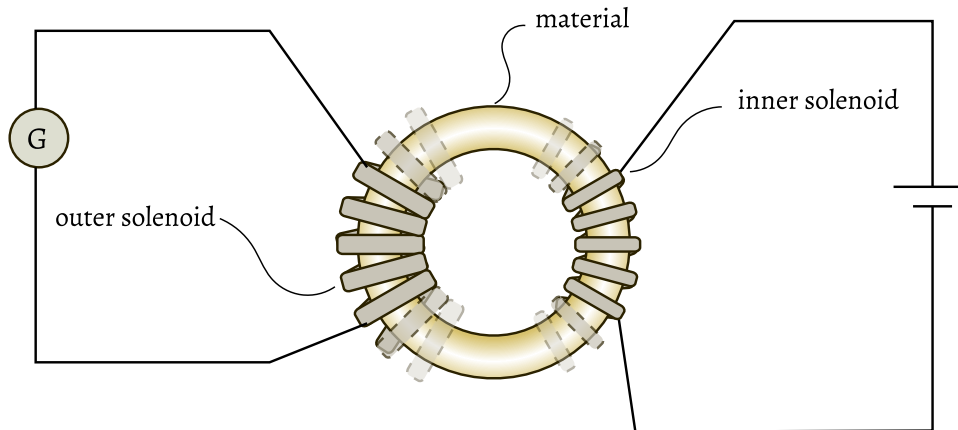


Figure 1: A Rowland ring.

3 Measuring Magnetic hysteresis

Magnets produce magnetic fields. If the net angular motion of the electrons in the material is aligned, the material produces a magnetic field. The ability of a material to retain its magnetic field is dependent on the structure of the material. To illustrate this ability, we usually draw an hysteresis curve.

An hysteresis curve is made by using a Rowland-ring. This is a ring made of the material in question with copper wire wound around it. The copper wire acts as a solenoid and is used to set up an external magnetic field throughout the ring (figure 1). This field is felt by the material which becomes magnetized in the same direction as the field. When we turn off the field, the material retains some magnetization if it is actually a magnet.

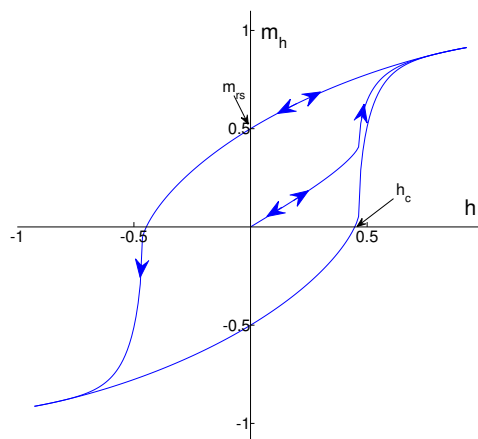


Figure 2: Theoretical model of magnetization M of the material, against external magnetic field H . Starting at the origin, the upward curve is the initial magnetization curve. The downward curve after saturation, along with the lower return curve, form the main loop. The intercepts h_c and m_{rs} are the coercivity and saturation remanence. Note that this curve shows the magnetization as a function of the external field H , while we will measure the total magnetic field B as a function of H .⁵

By using an outer solenoid, wrapped around the ring once more, we may measure the total field from the magnet and the inner solenoid. By clever use of this apparatus we can draw an hysteresis curve, where

⁴See Wikipedia, Lenz's law, http://en.wikipedia.org/wiki/Lenz%27s_law (as of Oct. 17, 2012, 11:26 GMT+1).

⁵Image source: <http://en.wikipedia.org/w/index.php?title=File:StonerWohlfarthMainLoop.svg&page=1>

one example of such a curve is shown in figure 2. The curve shows the magnetization of the material as a function of the external magnetic field and tells us by its shape whether the material retains its magnetization and how easy it is to magnetize.

3.1 Theory

By applying current to the inner solenoid, we produce an external magnetic field,

$$H = \frac{NI}{2\pi R} \quad (1)$$

where I is the current through the inner solenoid and N is the number of windings. R is the radius of the ring. We let the ring have thickness $2r$ and note that if $r \ll R$, then H will be constant inside the ring.⁶

To measure the total field, B , which is the sum of the field from the magnetization of the magnet, M , and the solenoid, H , we use an outer solenoid, placed outside the inner solenoid. We are not sending current through this, but are instead measuring the voltage from end to end of the outer solenoid.

Since the magnetic field through a solenoid cannot be measured directly from voltage, we need to use some equipment to integrate the voltage over time. This is because it is only a change in the magnetic field that creates an electric field by Faraday's law,

$$\oint_{\partial\Sigma} \mathbf{E} \cdot d\mathbf{l} = - \int_{\Sigma} \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{A}. \quad (2)$$

or in terms of the electromotive force, \mathcal{E} ,

$$\mathcal{E} = -N \frac{d\Phi_B}{dt} \quad (3)$$

where N is the number of windings on the solenoid.

By taking the integral of the voltage over time, we should find the change in magnetic flux:

$$\int_{t_1}^{t_2} \mathcal{E} dt = -N\Delta\Phi_B \quad (4)$$

The magnetic flux is proportional to the magnetic field B , so the curve will be pretty much the same even if we draw $\Delta\Phi_B$ and not ΔB . (If we want to actually calculate something, we would have to know the radius and thickness of the ring).

Don't worry, you don't have to calculate the above integral yourself. Thankfully we have equipment that does this quite easily for us. This equipment is known as an integrator (who would have guessed?) and works either by some clever circuitry or by measuring the voltage at discrete time intervals and summing it all up. We won't go into details about this, but if you're interested, you may read more about it [on Wikipedia](#).

3.2 Procedure

What we want to do now is to plot the total magnetic field B as a function of the external magnetic field we produce from the inner solenoid, which we denote as H . We see that there are now two proportionalities we may use. We have

$$\Delta B \propto \Delta\Phi_B \quad (5)$$

from that $\Phi_B = \iint_S \mathbf{B} \cdot d\mathbf{S}$, and

$$\Delta H \propto \Delta I \quad (6)$$

⁶If you haven't already, this might be good time to read up on the relationship between H and B . There is some good information about this [on Wikipedia](#).

from Ampere's law, $\oint_C \mathbf{H} \cdot d\boldsymbol{\ell} = I_{f, \text{enc}}$.

If we plot the change in I on the x axis and the change in Φ_B on the y -axis, we are to some proportionality plotting B as a function of H .

This gives rise to a few interesting observations we can make:

- We may see if there is any magnetic field left from our material when the external magnetic field is zero ($H = 0$).
- If we turn the magnetic field around in the other direction $H = -H_{\text{max}}$, we can check if the field from our material will follow along and remain in the other direction after turning off the external field.

To test this, you should do the following:

1. Find a Rowland ring.
2. Connect the inner solenoid to the current source.
3. Connect the outer solenoid to the integrator.
4. Turn the current down to 0 and up to I_{max} .
5. Turn the current down to $-I_{\text{max}}$.
6. Turn the current up to 0 again.
7. Repeat this a couple of times before you make your final recording.
8. Repeat the experiment with a different current. Try the currents $I = 0.5 \text{ A}, 1 \text{ A}, 4 \text{ A}$.

Equipment list

- Coils with wire-connectors
- Wires
- Bar magnets
- Datalogger
- Round neodymium magnets
- Hysteresis setup
- Steel tube

Prelab questions

- What is induction?
 - The production of a magnetic field from a moving electric field.
 - A dream inside a dream inside a dream.
 - The force on a magnetic charge moving in an electric field.
 - The production of an electric current across a conductor moving through a magnetic field.
 - The production of a magnetic field from moving electric charge.

- What does Lenz's law state?
 - That magnetic flux is induced by electric fields that are antiparallel to each other.
 - That induced electromotive force (emf) gives rise to a current whose magnetic field is in the same direction as the change in magnetic flux.
 - That induced electromotive force (emf) reduces the electric field around magnetic flux.
 - That an induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux.

- What is an hysteresis curve?
 - A curve showing the magnetization of a material as a function of an external magnetic field.
 - A curve showing the curvature of the magnetic field of the Earth.
 - A curve showing the electric field of a material as a function of an external magnetic field.
 - A curve showing the path of an electron through a magnetic field.
 - A curve showing the curvature of the Earth during magnetic storms.

- How can we find the magnetic flux by measuring voltage on the outer solenoid of a Rowland ring?
 - By integrating the current over time.
 - By integrating the voltage over time.
 - By sending a magnetic field through the Rowland ring and dividing by the diameter.
 - By taking the time that is needed to charge a capacitor using the Rowland ring.

Questions:

1. Why does the sign of the voltage change while the magnet falls through the solenoid?

2. Why is the shape of the curve different before and after it cuts through $V = 0$? (Except from being negative on one side and positive on the other.)

3. How does the height you drop the magnet from change the shape of the curve? Why?

4. How does the drop height affect the integral? Why?

5. How does the direction of the magnet affect the curve? Why?

Questions:

6. Why does the piece of steel fall straight through the tube while the magnet does not?

7. Was this experiment fun to observe? (10 point question, you better get this one right!)

Lab journal: Magnetism and induction
Measuring Magnetic hysteresis

Name: Date:.....

Questions:

8. What does the plot, known as an hysteresis curve tell us?

9. What happens when you increase the current and make a new curve? Why?

10. Is the material ferromagnetic, paramagnetic, diamagnetic or not magnetic at all? How can you see this from the hysteresis curve?