Performance:
Report:
Total:

Physics 212-6

Faraday's Law

NAME: ______________________________ ☐

STUDENT ID ______________________________ ☐

LAB PARTNER(S): ______________________________ ☐

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Check the box next to the name of the person to whose report your group's data will be attached.

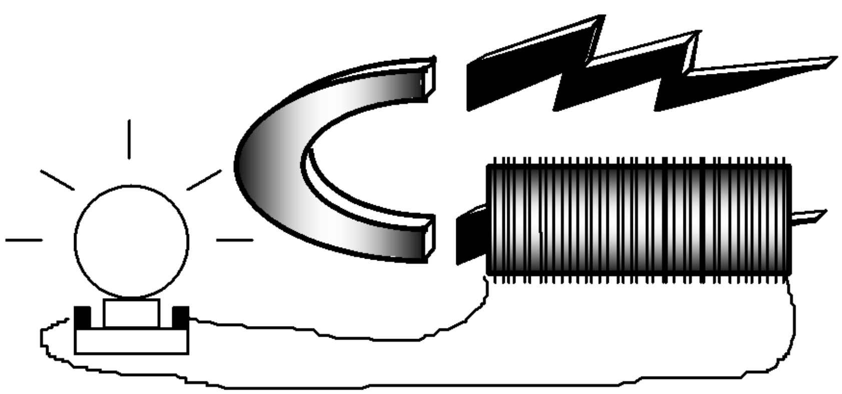
LAB SECTION: ________________________

INSTRUCTOR: ________________________

DATE: ________________________

TABLE: ________________________

(YOU WILL BE TAKEN 3 POINTS IF TABLE IS VACANT.)



Written by Beda, Dick, Hearn, Hertzog, Makins & Weissman, modified by Xia Huanxin for ZJUI

Physics Lab 212-6

Equipment List
Bar magnets (3)
Function generator
Voltage probe
5 m long wire with banana ends
Tape (electrical)
Rods for supporting generating coil and for "magnet drop" (three—one 5 ft. vertical, two 1 ft. horizontal)
Clamps; table clamp, 3 right angle clamps, and a large claw clamp
Bucket to catch the falling magnet
Springs for oscillating magnet activity
4000 turn coil and red LED

Computer File List
Capstone file "212-06 Induced EMF"

Physics Lab 212-6

Faraday's Law

Generating Electricity Using Magnetic Fields

To find out

- The concept of magnetic flux
- What happens when the magnetic flux through a wire loop is changed over time
- Some important practical applications that stem from the law of induction and magnetic field interactions

Preview

- Use a bar magnet and a wire loop to perform qualitative magnetic induction experiments
- Systematically vary the essential aspects of Faraday's Law of Induction
- Build an AC generator and motor

WARNING: This Investigation Utilizes Some Relatively Strong Magnetic Fields That Can Be Hazardous to Your Possessions. Be Sure To Keep Computer Monitors, Watches, Credit Cards, and Student IDs Away From The Magnets.

Activity 1 Magnetic Flux and Faraday's Law of Induction

The magnetic flux Φ through a loop of wire is given by

$$\Phi = \int \mathbf{B} \bullet d\mathbf{A} \qquad \text{(Eq. 1)}$$

where **B** is the magnetic field passing through the surface of area A enclosed by the loop. The direction of the vector $\boldsymbol{A}$ is normal to the surface.

For a flat surface in a constant field, this reduces to

$$= \boldsymbol{B} \cdot \boldsymbol{A} = B_{\perp}\ A = BA\cos\theta \qquad \text{(Eq. 2)}$$

where $B_{\perp}$ is the perpendicular component of the magnetic field passing through the surface.

Does a magnetic field cause an *EMF* and current to flow in a loop of wire?

1. Choose a solenoid (the 2000 loops one) or wind it yourself. If you want to wind it:
   - Tightly wind a short, 3-5 cm wide coil on the ≈ 15 cm long PVC tube, as shown in Figure 1 below. The idea is to place as many loops as possible on the tube, keeping them very close together in a double or triple layer. (Why do we want a short coil instead of a coil that covers the whole tube?) Count each loop you wrap around the tube. Record the number of loops for each layer as you wind.
   - Place a piece of tape over the coil to hold it together.
   - Record the total number of loops in the coil below:

     number of loops N = __________ [loops]

2. Set up the software.
    - Open the 212 Lab Files folder on your desktop.
    - Double-click on the file called "212-06 Induced EMF."
    - The voltage probe should be connected to the sparklink Air and the potential readout should be displayed.
    - Clicking on the Record button to start the software. The probe will zero in a few seconds.

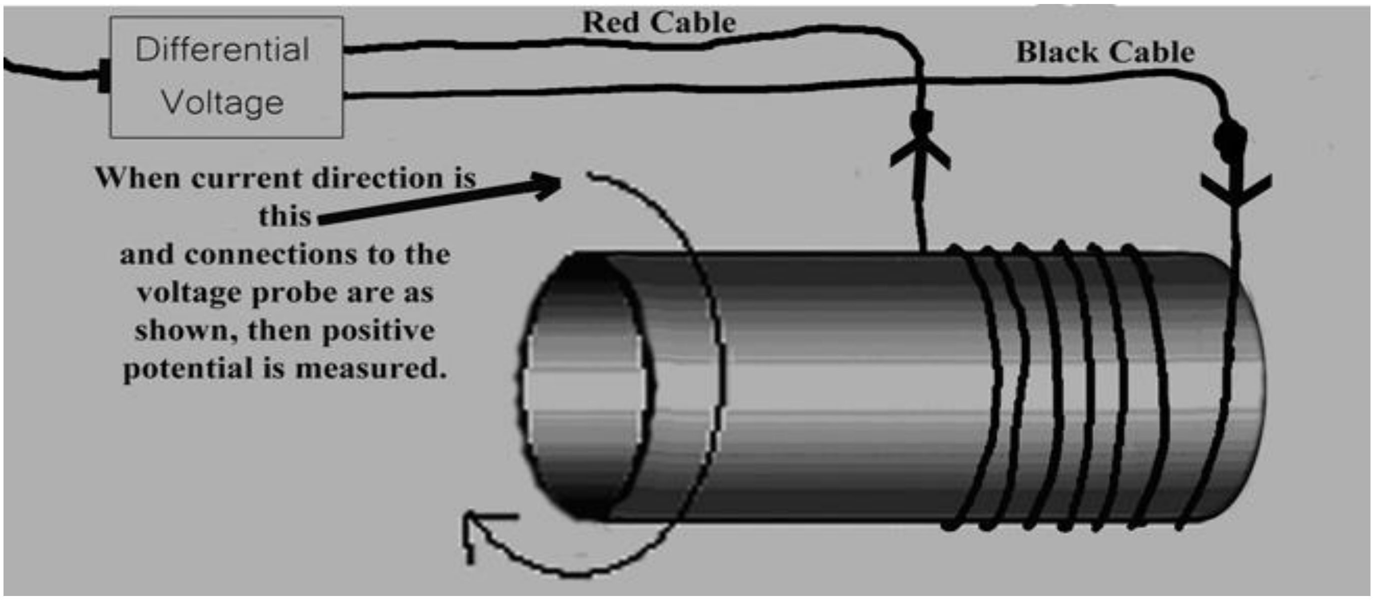


Figure 1. Configuration to measure current through a coil

3. Connect the solenoid to the voltage probe.

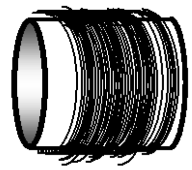
- **Connect the coil leads to the voltage probe in such a way that the voltage probe measures a positive voltage when the current in the coil flows clockwise around the tube when looking through the tube from the left as shown in Figure 1 above.** Note that the voltage probe measures a positive voltage when current flows into the voltage probe through the red wire and out of the voltage probe through the black wire.

- **Note: For the 2000 loops solenoid, it's transparent,** so the winding direction could be seen, please infer it yourself if necessary.

Note: you can monitor the current if connect the two jacks (holes) in the probe blue box.

In your text, the phrase "induced current" is used to describe a situation where current flows in a circuit in which there is no battery or other direct source of *EMF* (*Electromotive Force*) in the circuit. Your setup has no visible *EMF* source. You have created the same type of device that Faraday and Henry used to explore the effects of magnetic fields on loops of wire.

Prediction Draw in a bar magnet and its magnetic field lines in the space below. Position the magnet so that a *maximum magnetic flux* passes through the loops. If a magnet is placed in this position at rest, would an EMF be induced in the coil plus voltage probe circuit? Explain your answer.



4. Take data with the magnet at rest. Please use the rare-earth magnet if your solenoid doesn't have many loops. If you use the 2000 loops one, then any magnet is ok.
   - Place your bar magnet in a position which you believe to maximize the magnetic flux through the loops and rest it there.
   - Click on **Record** to start graphing and observe the *EMF* in the circuit.

Q1 What did you observe?

5. Take more data – this time with the magnet moving.
   - Start the graphing again and move the magnet quickly back and forth inside the coil. Also, try starting the magnet several centimeters away from the coil and passing it all the way through the coil (this simulates the cart problem of the prelab).

Q2 What did you observe?

6. Explore the dependence on the nature of motion.
   - Read Questions 3-5 and the note preceding them before proceeding.
   - Remove the magnet from the coil and grasp it at one end.
   - Start graphing and explore each question by performing an appropriate experiment. Discuss with your group what to do in advance and make sure that you briefly describe your procedures in each case.
   - Plan to print one graph and annotate it to support your claims. You might need to display data from two or more of your experiments on this same graph. You can do this by choosing  and tick the Run #. New collected data will then appear in a different color on the computer screen. On the printout you can label what data applies to which experiment you perform.

Note for questions Q3 through Q5 below: Refer to Figure 1 as your orientation reference. The pushing of the magnet into the coil is from the left in the figure (i.e., the magnet moves right). Pulling the magnet out of the coil is also from the left in the figure (i.e., the magnet moves left).

Q3 How does the induced *EMF* depend on the speed with which you push in or pull out the magnet?

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Q4 How does the sign of the induced *EMF* (positive or negative) in the coil depend on the direction of motion of the magnet when you have the south pole facing right (i.e., the south pole enters coil first when pushing the magnet into the coil from the left)?

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Q5 How does the sign of the induced *EMF* in the coil depend on which magnetic pole first enters the coil?

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7. Print/Send your data.
   - Adjust your graph if necessary to get a good display.
   - **Take photos of** your results for your group; include a title and your table/group.
   - Annotate your printout, showing where you obtained your answers for **Q3**, **Q4**, and **Q5**. Send photos in WeChat group.

Q6 When the north end of the magnet is plunged into the coil, does the induced current flow clockwise or counterclockwise as viewed looking into the side the magnet is plunged? How could you have predicted this?

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Prediction	How does the induced *EMF* in the coil depend on the *strength* of the magnet plunged through the coil? ____ ____

8. Explore the dependence of the induced *EMF* on the strength of the magnet. (Please use the 4000 loops solenoid and the normal magnets)
    - Find a second magnet and hold it side by side to the first so that its north pole touches the other's south pole. It should look something like:

    - Start graphing and explore the *EMF* in the coil when you plunge this magnet pair inside it.

Q7 What did you observe? Explain.

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9. Further explore the dependence of the induced *EMF* on the strength of the magnet.
    - Configure the two magnets so that the north poles touch and the south poles touch:

    - Start graphing and explore the induced *EMF* in the coil when you plunge this magnet pair inside it.
    - Try it with three magnets configured so that the north poles all touch and the south poles all touch.

Q8 How did your results compare with your prediction? How does the induced *EMF* depend on the strength of the magnetic field?

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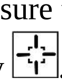
As you hopefully discovered above, the induced *EMF* in the coil depends on the speed with which you change the magnetic flux through the loops as well as the magnitude of the magnetic field. Therefore, to test how the induced *EMF* depends on the properties of the coil itself, you will have to carefully control the speed. Remember that objects dropped from the same height will fall at the same acceleration *independent of their masses.* So, you can use gravity to compare the induced *EMF* from the magnets as they fall through the coil from a fixed height. To get a strong signal, you will use the rare-earth magnet.

10. Prepare the equipment.
    - **<u>Make sure you have the bucket of sand (or sponge) positioned to catch the falling magnet.</u>** Since bar magnets are easily demagnetized by mechanical shocks, do not drop magnets on the floor.
    - Here we **use the normal bar magnet.**
    - Hold your coil and make it point vertically. The coil should be in the open mouth of the bucket. See the coil position in Figure 2. Be careful not to make the coil fall.
      Hold one end of the magnet just above the rim of your tube. See Figure 2.

Figure 2. Configuration for dropping magnets from a fixed height through the coil

11. Take some data.
    - Start graphing. When you get to about the one-second mark, let the magnet drop. Stop the graphing and measure the highest EMF induced by the drop. Find the peaks on your graph by . A box will appear that will display the data. You may wish to expand the scale of your graph for better analysis.

      1st peak induced *EMF* (bar magnet) = ___________ [V]

      2nd peak induced *EMF* (bar magnet) =___________ [V]

Q9 Look carefully at your data. Do you see any difference between the magnitude of the first peak (from the magnets entering the coil) and the second peak (from the magnets exiting the coil)? Explain the physical origin of any differences you see.

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12. Change the number of loops.

- Choose another solenoid (2000 loops).
    - Carefully re-establish your experimental starting points. Hold the bar magnet at the same height above the coil as before.
    - Repeat the experiment described above for bar magnet and record your result.

1st peak induced *EMF* (2000 loops with bar magnet) = ____________ [V]

2nd peak induced *EMF* (2000 loops with bar magnet) = ____________ [V]

Q10 Compare your result to those from the original coil. What general relation applies between the induced *EMF* and the number of loops in the coil?

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In the last few experiments, you have been exploring the nature of *Faraday's Law of Induction*. As we shall see in a few moments, this important phenomenon (together with *Oersted's Discovery*, which was probed in the previous lab) has revolutionized modern life.

Faraday's Law is stated mathematically as

$$\varepsilon = -N\,\frac{\mathrm{d}\Phi}{\mathrm{d}t} \qquad \text{(Eq. 3)}$$

where ε is the induced *EMF*.

In the series of experiments that you have just performed, all aspects of this law have been explored qualitatively. You actually measured *EMF*, but if you would rather measure the current, you could use Ohm's law

$$\varepsilon = IR \qquad \text{(Eq. 4)}$$

where R is the resistance (in this case just the resistance of the wire and probe) and I is the current in the circuit. Thus, measuring *EMF* is the functional equivalent of measuring I.

Combining these equations we see that the current would depend on flux change according to:

$$I = -\frac{N}{R}\,\frac{\mathrm{d}\Phi}{\mathrm{d}t} \qquad \text{(Eq. 5)}$$

Activity 2 Induced Electricity that Works

Up to now, you've seen evidence of induced *EMF* as measured data from a voltage probe. In this activity, you will get a chance to see light produced by an LED in series with a large coil of 2000 turns when an *EMF* induced by you is of the correct polarity. See below the couple views of the coil and LED together.

An LED is a Light Emitting Diode. Like all diodes, it will conduct appreciable current only in one direction when the applied voltage is the correct polarity and within the specs of the diode. The voltages you will produce here are within the specs, so the diode will only light up when the applied voltage is both the right polarity and high enough to produce light (i.e., current can only flow in one direction and the LED will light only when enough current flows through it).

1. Light the LED.

    - Use a normal magnet to check the poles of rare-earth magnet.
    - With the coil and LED exactly set up as in the pictures above, try to light the LED by inserting a pole end of the rare-earth magnet about half way into the coil and then rapidly pulling it out of the coil. Reverse poles if necessary.
    - Try also pulling the rare-earth magnet out from the other end of the coil. Again, reverse poles if necessary.

Q11 The coil in the pictures is wrapped from its right banana jack (the red one) in an anticlockwise direction (in the view of the picture above) and ends at the left banana jack (the black one). The question for you is: which direction is the current flowing in the LED when it lights up? Left to right? Right to left? Explain how you know this using what you learned in Activity 1.

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Activity 3 Do-it-Yourself Electricity

Faraday's Law of Induction tells us that an *EMF* is generated in a coil when a *changing magnetic field* interacts with the coil. Here you build a simple little device that automates the changing magnetic field. That is, you make a real *power generator*! You will use springs with your magnet attached as in Figure 3 to achieve a continuously oscillating magnetic flux in your coil.

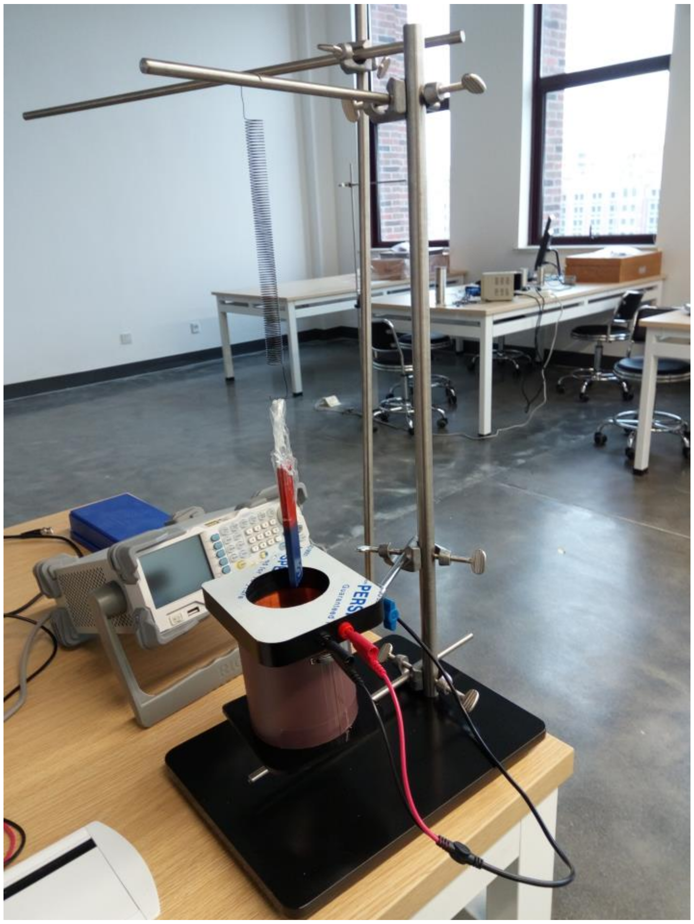

Figure 3. Setup for oscillating magnet activity

WARNING: These Springs Can Fly Off! Be Careful!

1. Set up the hardware.
    - Choose the 4000 loops solenoid and secure it with a claw clamp to the vertical rod at your station as in Figure 3 above.
    - Attach the magnet with loops of string on its poles to the springs at one end by using tapes. Hang one spring on the top tape ring.
    - Adjust the height of the coil so that one pole of the magnet is at the same height as the up-plane of the coil when the spring/magnet system is at equilibrium as in Figure 3 above.
2. Set up the software.
3. Run the experiment.
    - Gently start a small oscillation of your magnet by lifting it straight up about one inch or so and letting go vertically. Make sure the magnet does not hit the inside of the tube.
    - Start graphing.
4. Print/Send your results.
    - Adjust your graph if necessary to get a good display.
    - Give a title to your plot. Put your group's names on it, and **Print/Send…** out one copy of your results for your group.

Q12 What did you observe? Is it a periodic motion? If yes, what's the frequency?

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Q13 From where does the *electrical energy* that this system produces come?

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Q14 What practical device could be built using the principle of this experiment?

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Q15 In the absence of friction in the *spring - magnet mechanical system*, would the oscillation go on forever? Explain your reasoning.

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Now that you have discovered how to turn mechanical energy into electricity, it might be a good idea to find out another way electrical energy might be used to do work.

Activity 4 Make it Move!

Prediction	You have seen that moving a magnet through a coil produces a changing electrical potential difference between the two ends of the coil (thus producing a current in the circuit). What would happen if you instead put the magnet-spring system at rest and used an external source to apply a changing potential to the coil? ____ ____

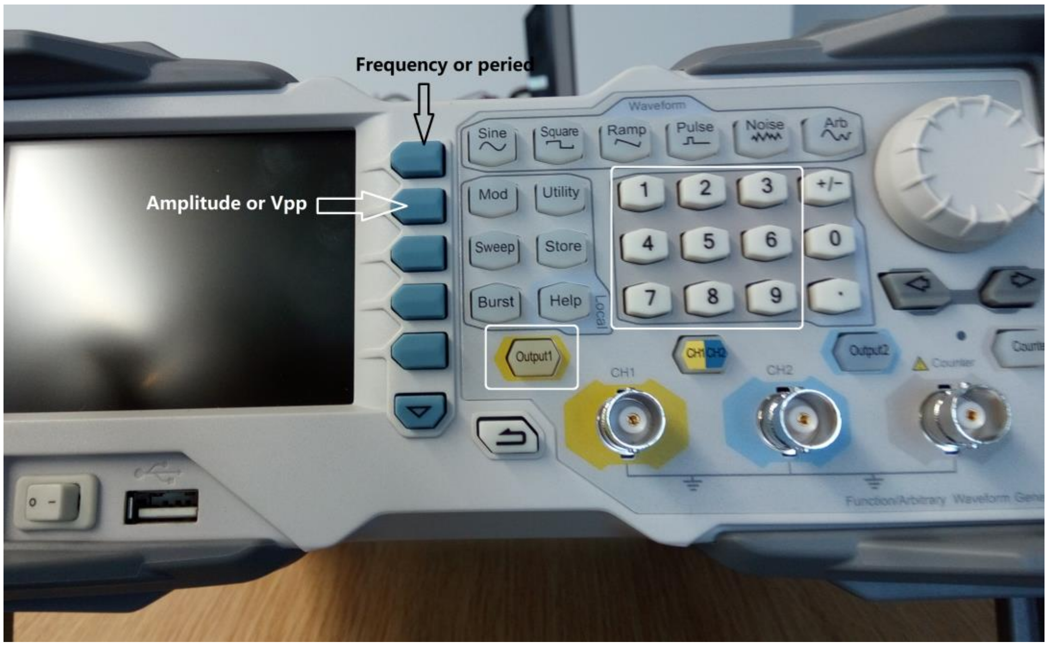
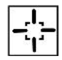


Figure 4. The function generator

You will be using the function generator in Figure 4 to produce the external oscillating potential to test your prediction. In order to check whether the spring will respond to this situation, it will be important for the output of the function generator to match the natural, or *resonant*, frequency of the spring-magnet system.

Recall from Physics 211 that giving a momentary impulse to a spring-mass system will cause the system to oscillate at a certain frequency f_o determined by the spring constant and the mass. Just as one needs to give a push to someone riding on a swing at just the right moments, giving impulses to a spring system in tune to its natural frequency will allow the energy of each impulse to stay in the system. (Otherwise, you would be fighting against the oscillating system.)

The natural resonant frequency of the magnet/spring system can be obtained by computing the frequency of oscillations of the potential voltage data you obtained previously. **Note** that since the bar magnet is a dipole, *each* oscillation of the magnet would have produced *two* maxima (and two minima) in the potential data if both poles of the magnet oscillated through the mid-plane of the coil. You were instructed to have only one pole of the magnet oscillate through the mid-plane, so the frequency of your data should match the resonant frequency of the magnet/springs mechanical system.

1. Determine the resonance frequency of the spring-magnet system.
    - Use your data from the previous activity or take some more data and find the resonance period T_o by counting the number of complete *spring oscillation* cycles, and then dividing the time elapsed between the beginning of the first oscillation and the end of the last by the number of spring oscillation cycles. To obtain good readings of the beginning and end times, choose  and then carefully point at the appropriate points on the waveform with the mouse and read the times displayed in the data box on the screen.

      Resonance period T_o = __________ [sec]

    - Take the reciprocal of the period to find the frequency f_o.

      Resonance frequency f_o = __________ [sec^{-1}]

2. Set up the driver.
    - Run the generator.
    - Press the waveform button on the top row to choose sine waveform.
    1. The first (top) blue button is used to choose frequency and period. Press it, when the "frequency" brightens, you can set the frequency by the number dial panel and choose the unit by the blue button.
    2. The second blue button is used to choose the peak value of the wave. When the "amplitude" brightens, you can set the Vpp. Vpp means the voltage from peak to peak. It suggests the Vpp is around 5-10 Vpp. Actually small Vpp also works, only takes longer time to start oscillating.
    - After you have set frequency and amplitude, connect the solenoid through output 1 by the BNC-banana line.

3. Test your prediction.
    - Steady the magnet on the springs. As before, one pole of the magnet should be at the same height at equilibrium as the top-plane of the coil. Then press the output1 button. The generator will output the signal. (**Don't run it too longer, the oscillation will be too great and the magnet may fly out! Resonance!**)

Q16 Did your observations agree with your prediction? Discuss.

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4. How important is the correct frequency?
    - Steady the magnet on the spring.
    - Set the frequency to one-fifth of the resonant frequency. Leave the amplitude knob untouched.

Q17 What happens? Why is the response different?

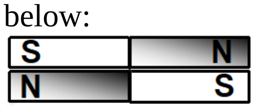
Q18 What practical device might be built upon the principle of driving a spring-magnet system at its resonance frequency using an external electrical generator? What could be its uses?

CLEAN UP CHECKLIST

☐ Quit any computer programs and do not save the data or calibration. Do not turn off the computer. Turn off the function generator. Disconnect, unwrap and put away the wire.

☐ Collect the papers onto which data was taken (and annotated) and attach them to one of the lab reports.

☐ Make your setup look neat for the next group. So as not to ruin the magnets, store them two together, as shown below:



☐ Staple everything together, make sure you have answered all the questions and done all the activities, make sure the first page is completed with lab partners' names and check boxes. Hand in your work before you leave.