Speaking of Electricity & Magnetism

Pre-Lab: Sound Waves and Their Generation from Speakers

A Bit of History

"Mr. Watson, come here! I want to see you!" These words were spoken by Alexander Graham Bell to his assistant, Thomas Watson, as the first transmission through a working telephone. This fact is something that you probably learned long ago, back in your youth. What you most likely didn't learn was that in order to invent his telephone, Bell first had to invent the speaker and microphone. These devices allowed Bell to turn a mechanical sound signal into an electrical signal that could be carried from one phone to the next via a conducting wire.

Today we are all too familiar with speakers since they can be found in everything from cars to earphones. The functional mechanism behind a speaker is the interplay between an electromagnet (a magnet produced by a coil of wire carrying an electrical current) and a permanent magnet (like the things you stick on your refrigerator) placed in its center.

What Is Sound and How Do Humans Perceive It?

From the moment a baby is born it can hear sounds coming from its surroundings. With luck, the ability to perceive sound is something that lasts during a human's entire life. Of course, this is nothing new to you, but you might wonder exactly how sound travels from the emitter, enters our ears, and is communicated to our brain.

Before we can proceed, we need to know a bit about the propagation of sound through a medium (unlike light, sound requires a medium to travel). We are usually interested in how sound travels through air, and it is the propagation of sound through air that we discuss here. However, sound can travel through solids and liquids as well, and the word "air" could easily be replaced with "plastic" or "water". Now, getting back to the point, generally a collection of air molecules are hanging out at *atmospheric pressure* (see p. 10 of Unit T in Moore or p. 620 of Young & Freedman for a description of gas pressure). When these molecules are in contact with a surface, they exert this atmospheric pressure on that surface. If the pressure in the air were to increase, the pressure on that surface would increase, causing the surface to be compressed. Likewise, if the pressure in the air were to decrease, the pressure on the surface would decrease, allowing the surface to expand.

Now, you might ask, "What the heck does this have to do with sound?" Well, it turns out that sound waves are a series of high and low pressure areas that travel through air (see Figure P1). So as a sound wave reaches a surface, the pressure that the air exerts on that surface varies. This series of increasing and decreasing pressure causes the surface to expand and contract, or vibrate.

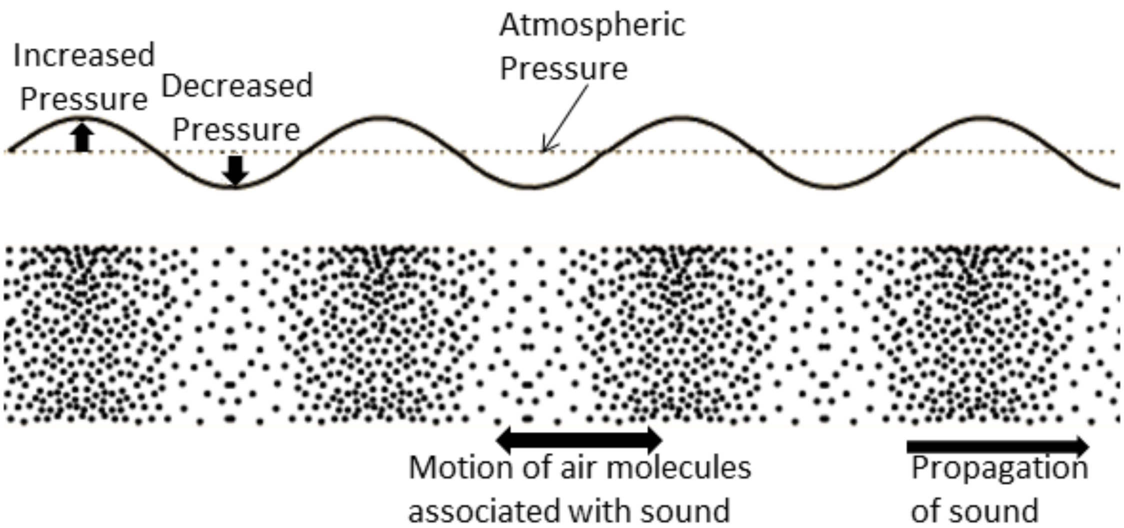

Figure P1: As a sound wave propagates through the air, it compresses and expands the gas molecules in the areas of high and low pressure, respectively. The effects of this compression and expansion can be seen in the Sound Wave Animation which you can access from the Pre-Lab Links on the lab website.

The phenomenon described above is the basis for how the human ear works. When a sound wave enters the ear, it impinges on the ear drum. The ear drum responds to the alternating high and low pressures by vibrating back and forth (see the Sound Wave Animation on the lab website). This vibration is communicated to an area of the inner ear called the cochlea. Inside the cochlea, there are a series of hair cells that respond to this vibration by sending electrical pulses to the brain, thus creating the perception of sound.

An interesting physiological note is that as humans age, they gradually lose the ability to hear high pitched sounds, a process called *presbycusis*. This process is described in a recent Scientific American online article.

Do This: Visit the following website and read the article: http://www.scientificamerican.com/article.cfm?id=bring-science-home-high-frequency-hearing&page=1. Follow the link (in the "Materials" section of the article) to npr.org where you should download the mosquito ringtone.

PL1. Can you hear the sound?

PL2. Find someone who is older than you - can they hear the sound?

PL3. Describe the difference in the effects of presbycusis and noise-induced hearing loss.

The Creation of Sound by a Speaker

We are now comfortable with the fact that sound is a traveling, mechanical wave. But now we start to wonder, what exactly creates this wave? The creation of a sound wave can be done in a variety of ways. For instance, if you strike your desk with your fist you will hear a sound. The act of striking the desk makes the desk vibrate (granted, it's a very small vibration that probably can't be seen by your eye). When the desk vibrates, it alternately compresses and expands the air near its surface. This compression and expansion of air is the creation of the sound wave that propagates to your ear.

In this week's lab, we will look at the creation of sound by a speaker. The sound that emanates from a speaker is due to the movement of a *diaphragm*, which compresses and expands the air around it. The movement of the diaphragm is actuated by an electromagnet attached to it. An electromagnet is a magnet which is created by a current-carrying coil of wire. Figure P2 is a schematic of the magnetic field around an electromagnet like the one used in a speaker.

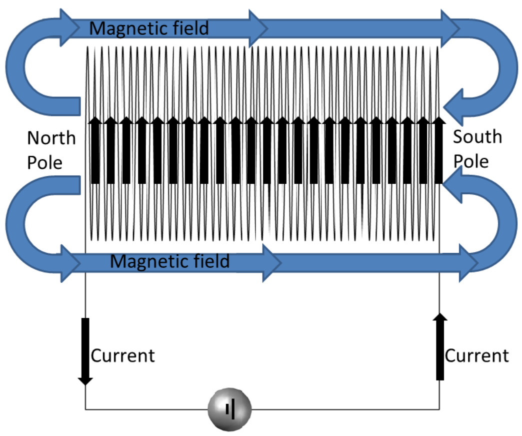

Figure P2: A current-carrying coil of wire. As the current passes through the wire, it creates a magnetic field that wraps around the coil as shown.

In addition to an electromagnet, every speaker also contains a permanent magnet. The permanent magnet creates a force on the electromagnet, causing the electromagnet and diaphragm to move. Since electromagnets are so important to the operation of a speaker, let's get more comfortable with them by playing with a computer simulation.

> **Do This:** Download and run the PhET simulation "Magnets and Electromagnets" from http://phet.colorado.edu/en/simulation/magnets-and-electromagnets. On the tab labeled "Bar Magnet", play around with the compass by positioning it at various locations around the magnet. Note: the direction of the magnetic field line points from white to red on the compass.
>
> PL4. Sketch the bar magnet, labeling the north and south poles. Draw the field lines surrounding the bar magnet.

PL5. Click on the box labeled “Show planet Earth”. Make a rough sketch of Earth, including North America. Draw the field lines that surround Earth.

Do This: Now move to the tab labeled “Electromagnet” and play around with the compass.

PL6. Sketch the electromagnet, including the current-carrying coil of wire. You should also draw the magnetic field lines surrounding the electromagnet.

PL7. Is your sketch in PL6 consistent with Figure P2? If not, why?

PL8. What happens when you switch the direction of the battery?

PL9. What happens when you change the number of loops in the coil? Use the field meter to quantify your answer.

PL10. Describe the behavior of the field lines when current source is AC instead of DC.

Part I: Building Your Speaker

The Story

It's late on a Wednesday night and your procrastination can go no further – you need to study for tomorrow's physics exam. Preparing to head to the library for a long night, you pack all the essentials: textbook, computer, coffee, headphones….wait, your roommate has stolen your headphones again! What to do? You *could* study without music, but who does that?! Using the knowledge gained in class, you know you can make your own headphones out of materials you have laying around your dorm room. Given one more chance to delay your studying, your procrastinating spirit wins and you decide to take advantage of this opportunity.

How Does a Speaker Work?

Before you begin you must remind yourself of the relationship between a current carrying wire and the magnetic field it creates. Imagine that wire carrying current I is wrapped into a coil which has N turns. It can be shown that the strength of the magnetic field inside this loop of wire is proportional to the number of turns of wire and the current, while it is inversely proportional to the radius of the loop, R (eq. E9.13 in Moore; eq. 28.17 in Young & Freedman)

$$|\vec{B}| = N\frac{\mu_0 I}{2R} \qquad \text{Eq. 1}$$

In order to probe this relationship, we are going to explore how speakers work. At their heart, speakers contain a diaphragm attached to a coil of wire that (at least partially) surrounds a permanent magnet – for a pictorial representation see Figure 1. When a current passes through the wire coil, a magnetic field is created inside the coil (this is commonly called an electromagnet). This electromagnet has a north and south pole just like a permanent magnet. The electromagnet feels a force from the permanent magnet in its center. In response to this force, the electromagnet and the diaphragm move. The movement of the diaphragm causes the gas near its surface (usually air) to be compressed.

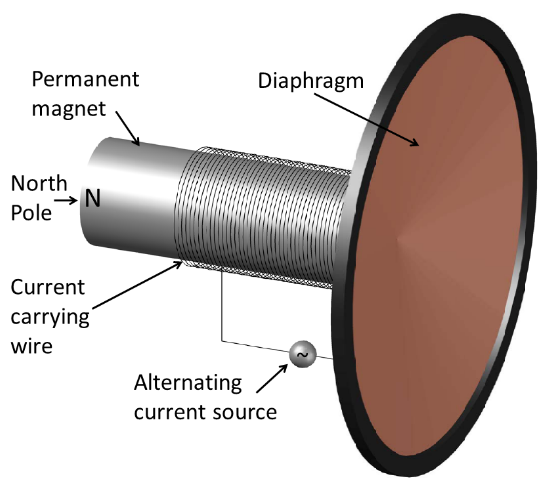

Figure 1: A speaker consists of a permanent magnet, a coil of wire, a diaphragm, and an alternating source of current. When a current is sent through the wire, an electromagnet is created. The permanent magnet inside the coil produces a force on this electromagnet causing it (and the diaphragm to which it is attached) to move.

When the direction of the current is switched, the magnetic field of the electromagnet also switches. This flips the direction of the force on the electromagnet and in turn, changes the direction it and the diaphragm move. Figure 2 shows snapshots of two instances in time when the current is in opposite directions. This movement allows the air near the surface of the diaphragm to expand. This process of compressing and expanding the gas is how a sound wave is created.

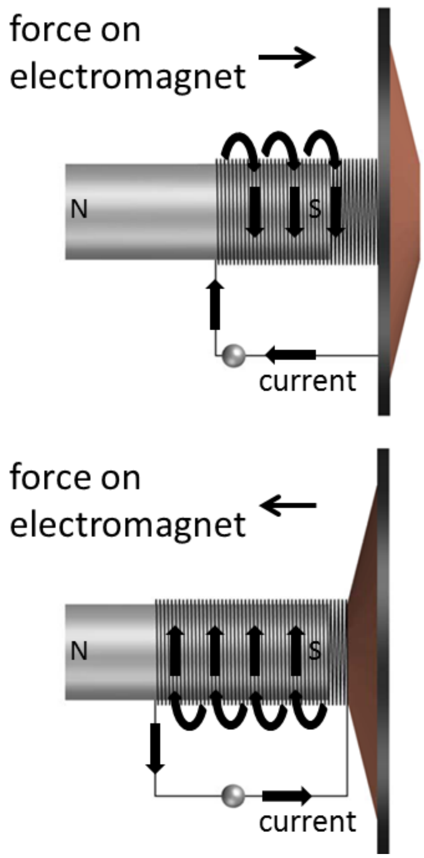

Figure 2: This is a snapshot of the side of a speaker at two instances of time in which the current is going in opposite directions. The field lines of the permanent magnet loop around it from north to south (left to right in the space above the magnet).

In the upper picture, the current loop is creating an electromagnet with field lines that loop from right to left in the space above the magnet, opposite to the direction of the field lines of the permanent magnet. This causes the two magnets to repel, pushing the electromagnet and the diaphragm to the right.

In the lower picture, the current loop is creating an electromagnet with field lines that loop left to right above the magnet, parallel to the direction of the field lines of the permanent magnet. This causes the two magnets to attract, pulling the electromagnet and the diaphragm to the left.

As the current switches back and forth the coil and the diaphragm get pushed back and forth, creating the sound wave that eventually reaches your ears.

Speakers as we know them are constantly vibrating back and forth. This is accomplished by hooking the coil of wire to a source of alternating current (think of this as a battery that switches direction at a specific frequency). As the current changes direction, the diaphragm follows by vibrating forward and backward at the same frequency, producing a sound wave at the frequency of the alternating current. You are now going to use this knowledge to create your own speaker.

Equipment

- Wire (3-meter section)
- Soda bottle
- Two magnets
- Balloon
- Duct tape
- Multimeter
- Headphone jack
- Music source (i.e. smart phone, computer, Walkman, etc.)
- Function generator with amplifier

1. Constructing and Understanding the Speaker

Do This: Use the balloon, bottle, magnets, and *3-meter section of wire* to construct a speaker. Keep in mind that when you are winding the wire you should make the windings as tight as possible. After you have wound the wire around the bottle, connect each end of the wire to one lead of the headphone jack.

1.1. After plugging the headphone jack into the music source, what do you hear? (If your TA begins to dance, don't be alarmed!)

Keep in Mind: You are about to connect your speaker to an amplified function generator so that you will have greater control over the sound produced by your speaker. There are about 15 speakers in this room. Please keep your speaker at a reasonable volume. Treat your speaker like a headphone rather than a boom box. You should only be able to hear it if your ear is at the end of the bottle.

Read This: There are a couple of knobs that will control the volume of your speaker: one on the function generator and one on the amplifier. The following instructions will explain how to adjust these knobs.

Do This: First, find the knob on the function generator (the big box) that reads **AMPL**. It's at the far-right of the function generator. Pull this knob toward you and turn it to 9 o'clock. **You won't have to touch it again.**

Do This: The large knob on the amplifier (the little box) reads **VOLUME**. This is the knob that you will use for the rest of the lab in order to change the amplitude of the current through your speaker. Begin by turning the current all the way down by turning the VOLUME knob counter-clockwise.

Do This: Disconnect your speaker from the headphone jack and connect it to the white leads coming from the amplifier using some combination of test leads and alligator clips.

Do This: Play with the speaker! Adjust the amplitude of the current using the VOLUME knob. ***Remember to keep the volume at a reasonable level.*** Adjust the frequency using the **FREQUENCY** and **RANGE** knobs on the function generator. (For more information on the RANGE and FREQUENCY knobs, see Appendix A.) Pay attention to how the sound changes as you turn the knobs. No need to write anything in your notebook; the point of this exercise is to gain some intuition for this process.

Read This: Now that you have a working speaker that you have total control over, let's test out a few physiological limits.

Do This: Set the function generator on a low frequency (~1 Hz). You should be able to see how this speaker is working. You may have to increase the volume significantly. ☠***Don't forget to lower the volume before you return the frequency to the audible range.***☠

1.2. Describe exactly what you see. How is this speaker functioning differently from the one that was described in the Pre-Lab?

1.3. What is the highest frequency where you can still clearly see the magnet moving? That is, at what frequency does the magnet start to look fuzzy?

☠**Warning:** In the next step, you are going to try to find the highest frequency you can hear. Remember that a loud sound can damage your ear even if you can't hear it. If you reach a frequency that you can't hear, **do not** increase the amplitude in an attempt to hear the sound, as this could damage your ear.

Do This: Use your function generator and speaker to test the highest frequency you can hear. Start by setting the frequency and volume knobs to produce a sound that is at a comfortable volume. Leave the volume knob there. Increase the frequency until you can no longer hear the sound. **Do not** increase the volume in an attempt to hear very high frequencies, as this can damage your hearing.

1.4. Record the highest frequency that you can hear.

1.5. Given what you read in the Pre-Lab, is your answer to Step 1.4 reasonable?

Part II: Testing the Magnetic Field

Equipment

- Wires (two 2-meter sections)
- PVC pipe
- Two magnets
- Balloon
- Function generator and Amplifier
- Vernier Microphone
- Multimeter

2. Testing the Magnetic Field

Hopefully by now you have deduced that if the strength of the magnetic field produced by the current loop increases, the permanent magnet will feel a stronger force, thus it (and the diaphragm it's attached to) will oscillate with a larger amplitude, which in turn makes the speaker louder. Now you want to test how each of the parameters in Eq. 1 affect the sound coming out of our speaker.

Read This: Let's try to connect the volume of the sound and the magnetic field in a quantitative way. There are a few ways to quantify the volume of a sound, one of which is by measuring the amplitude of the sound pressure wave (which is what you'll be doing). That is, you measure the pressure that the air exerts on the microphone. All else being equal, the pressure that the air exerts on the microphone should be proportional to the pressure that the diaphragm exerts on the air. Next, the pressure that the diaphragm exerts on the air should be proportional to the force that the magnetic field from the coil exerts on the diaphragm (through contact with the permanent magnet). Finally, the magnetic force is proportional to the magnetic field. Therefore, we should expect our measurement of the volume of the sound to be proportional to the magnetic field created in the coil.

Do This: Use the balloon, PVC pipe, magnets, and a 2-meter section of wire to construct a new speaker. Make sure the balloon is stretched taut. As you do this, **count the number of times you wrap the wire around the pipe**.

2.1. Record the number of turns of wire in your coil.

Do This: Set the frequency of the function generator to about 840 Hz. The FREQUENCY knob is not especially precise, though, so it will be necessary to use your multimeter to read the frequency using the "Hz %" setting. Connect one white lead from the amplifier directly to the *COM* input jack. Connect the other white lead from the amplifier to the *Hz* input jack. Then turn the knob on the multimeter to the "Hz %" setting. At this point you should be able to read a frequency off of the multimeter. Adjust the function generator until the frequency is 840 Hz.

Do This: Connect your new speaker, the function generator, and the multimeter so that you can measure the current through the speaker coil. You will be measuring currents over 400 mA, so make sure to use the *10 A* setting on the multimeter. You will also need to set your multimeter to measure AC current instead of DC current. Change from DC to AC by pressing the *Mode* button on the multimeter. **Don't forget that ammeters must be connected in series.**

2.2. Sketch the circuit that you have built.

Do This: Place the microphone inside of the PVC pipe. Notice that the microphone has two different diameters. It will be helpful if you position the microphone such that the transition between these two diameters is at the end of the PVC pipe. Note exactly where you have placed the microphone, as later you will be asked to place it in the same location. Open Logger Pro and get ready to take data. The default recording settings will work well for this experiment (10000 samples/s for 0.03 seconds).

Read This: When making a recording in the following steps, ***do not increase the current past 0.800 amps.***

2.3. Now use the microphone and Logger Pro to record the sound produced by your speaker. You will notice that *Logger Pro* displays a sinusoidal function. We are interested in the volume of the sound, i.e. the amplitude of the sinusoidal function. Using the fitting function in *Logger Pro*, find the amplitude of the sound wave. Repeat this measurement for different Function Generator amplitude settings, each time using an ammeter to record exactly how much current is passing through the wire, until your data convinces you of the relationship between current and volume. ***Don't increase the current past 0.800 amps.*** Create a data table in your notebook or print out a copy of a data table that you create on the computer.

Do This: Make a plot of the *Amplitude of the sound pressure wave* vs. *Current*. Do not print the plot quite yet.

2.4. What does the plot look like? Is that what you expect? Explain.

Read This: Keep your plot open so that you can add additional data to it. Do not print it yet.

Do This: Add the second 2-meter section of wire to the wire already on your speaker. Add the wire in series so that the coil is essentially 4 meters long. Do not add the wire in parallel. As you add the wire, count the number of times you wrap the wire around the pipe. After adding the second wire, place the microphone at the end of the PVC pipe. [**Important:** Make sure the microphone is in the same place as it was in the previous measurements.]

2.5. How many times (total number of turns) did your wire loop around the pipe?

2.6. Use your new speaker to repeat the measurements made in Step 2.3. Record the new data in your notebook or print out a copy of a data table that you create on the computer. Make sure to use nearly the same current settings you used in Step 2.3.

Plot

2.7. Add the data you have just collected to the plot you made earlier. Print out your plot and record the title as your response to this Step.

2.8. How well does the plot fit your expectations? Explain what matches your expectations. Additionally, explain what doesn't match your expectations. If anything does not match your expectations, do you have any ideas about why not? (Remember, you are not graded on how good your data looks. You are graded on how well you look at your data.)

2.9. Now that you have finished, your lab your TA wants to know: what was the goal of this lab and did you achieve it?

Head-Scratchers

Don't forget to complete the following problems. They should be at the end of your lab report. If you want to work on them during lab, start a new page in your lab notebook.

- 1.5
- 2.9

Appendix A: The Function Generator

This appendix will tell you everything you need to know about the function generator and even a little more. First, a function generator is used to produce a time-varying voltage (AC). Many features of the waveform can be varied, including: the amplitude, frequency, shape, and offset. The knobs on the function generator help to control these features of the waveform. Let's go through all of the knobs on the function generator to understand how.

FREQUENCY and **RANGE**

These two knobs are used as a team to determine the frequency of the function generator's output. To find the frequency of the output, all you have to do is multiply the number that the FREQUENCY knob points to by the value that the RANGE knob points to. (Then put Hz behind the result.)

For example, to produce a voltage with a frequency of 1 Hz, you should turn the FREQUENCY knob to 0.1 and set the RANGE knob to 10. As a second example, to produce a frequency of 20,000 Hz, turn the FREQUENCY knob to 2 and the RANGE knob to 10K.

Care should be taken when you change the range. If you are playing with a speaker at a sub-audible frequency, changing the range without lowering the amplitude or volume can result in a very loud sound that nobody wants to hear. When in doubt, lower the volume all the way before changing the range.

AMPL

That's short for amplitude. You will be instructed to pull the AMPL knob and turn it to 9 o'clock. All of the amplitude adjustments will be done using the amplifier. Actually, we need the amplifier because this function generator alone cannot produce a large enough current for us. The amplifier can increase the amplitude of the function generator's output while keeping the frequency unchanged.

FUNCTION

Feel free to play around with this knob. It changes the shape of the function generator's output. The different shapes sound different even if the frequency remains fixed. You might understand why after completing the Spectra Lab later in the semester.

When taking measurements, make sure the FUNCTION is set to the sine wave.

OFFSET

This shifts the whole wave up or down by some fixed number of volts. That's something that we don't need to do. Always keep this pushed in and pointed at 12 o'clock.

SWEEP Knobs

Don't worry about what these do. Just make sure they are pushed in.