Visualizing Sound with an Electro-Optical Eardrum

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As science educators, one of our important responsibilities is ensuring students possess the proper tools and accommodations to examine phenomena in a laboratory setting. It is our job to innovate methods enabling students with disabilities to participate in all aspects of investigations. This article describes an experimental accommodation allowing a deaf student to determine and plot the sensitivity of an electro-optical eardrum in the sound range of 10-150 Hz.

Introduction

An introductory physics laboratory experiment at my university guides students through several computer simulations investigating the properties of waves and wave interference. After the simulations, students are prompted to determine the minimum and maximum frequencies they can hear using a basic function generator and headphones. After administering a few lab sections, a thought crossed my mind and I wondered about my response as an educator to the following situation: If there was a deaf student in my class, what would he or she do when the other students were listening to headphones to determine their personal hearing sensitivities?

Starting at age seven, I spent many fun years at a daycare and met one of my best childhood friends, Jason. At the time, I do not think I comprehended what it meant that Jay was deaf. Unlike adults, young children do not need complicated discussion and communication skills to interact. We played together without his deafness ever becoming a barrier. As we grew closer, I was encouraged by Jay's mother to take American Sign Language classes so I could better communicate with him. After some classes I grasped many basic phrases and signs and already began interacting better with Jay. Having mastered the alphabet, even when I didn't know a word, I could always sign the letters to Jay. I still remember most of the signs, especially those for our favorite foods, including his favorite…spaghetti.

I remember his fascination with the bass lines in music. During movies, he could physically feel the pressure waves from the heavy bass sounds emanating from the theater speakers. Frequently he grabbed my arm so I would know something suspenseful was about to happen. It was the closest he could get to hearing and he loved it. Never was Jay shy when it came to talking about being deaf, nor did he ever ask for specific accommodation. But if Jay were to walk into my physics lab during this experiment, knowing it relied heavily on sounds and hearing, I cannot help but think he would feel left out. Not because he was deaf, but because he wouldn't get the same opportunity as the other students to experience every day sound and hearing from a scientific standpoint. This thought was the catalyst to the electro-optical eardrum.

The biophysics of hearing

The purpose of the auditory system is to convert sound (pressure) waves into electrical signals the brain can interpret. The ear is divided into the outer, middle, and inner ear as shown in Fig. 1. The outer includes the pinna, curved external cartilage, which "catches" sound waves and directs them into the ear canal. At the end of the canal, separating the outer and middle ear, is the tympanic membrane, more commonly known as the eardrum.[1] This taut membrane is pushed inward and outward via sound pressure waves.[2]

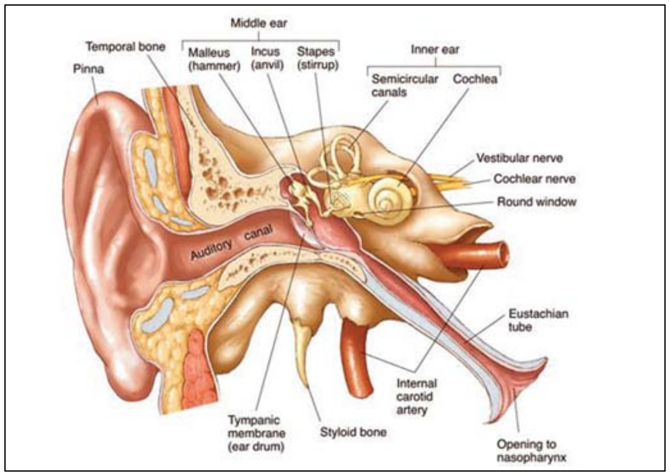

Fig. 1. Anatomy of the auditory system (Illustration ©Dave Carlson, Carlson-Art.com).

The three middle ear bones starting from the eardrum are the malleus, incus, and stapes. They are coupled to the eardrum and consequently vibrated when the eardrum oscillates.[3] All the vibrational energy of the eardrum is concentrated on the much smaller surface area of the ossicles. This increases the pressure 15 times, thereby amplifying the sound.[4] Once a sound propagates through the middle ear, it comes to the stapes faceplate, resting against the cochlea, which is the starting point of the inner ear.[5] Lining the length of the cochlea, which is a fluid-filled tube, are thousands of hair-like nerve cells. Each hair cell has a particular resonant frequency. When the stapes vibrates in the middle ear, it strikes the cochlear faceplate. This strike sends a compression wave through the cochlea, and as the wave travels, if its frequency matches with the natural frequency of any hair cells, those hair cells will resonate and vibrate with larger amplitude.[6] This increased movement initiates nerve cells to emit electrical impulses to the brain for processing.[7]

When one or more of these steps cannot be executed correctly, deafness occurs. There are two types of deafness:

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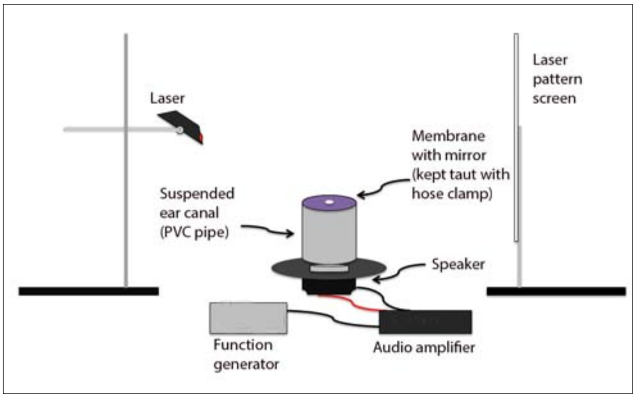
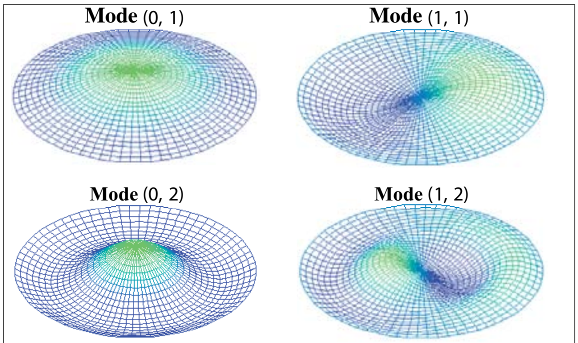


Fig. 2. Experimental setup.



Classification for labeling modes is (m, n), with m as the number of nodal diameters and n as the number of nodal circles where there is no displacement.

Fig. 3. Circular membrane modes.

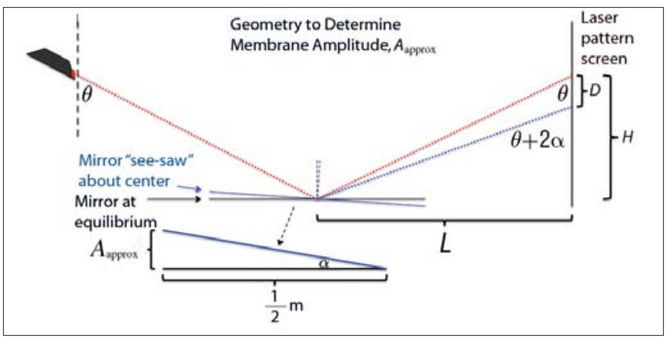


Fig. 4. Mode (1,1) light reflection.

conductive and sensorineural. Conductive deafness occurs when sound waves cannot enter the inner ear. Usually physical impedance, it can result from infection, eardrum perforation, loud noises, etc. Sensorineural deafness most commonly involves damaged hair cells, auditory nerves, or auditory processing in the brain. These can be caused by genetics, viral infections, inflammation, multiple sclerosis, and stroke.[8]

Electro-optical eardrum system*

The experimental setup for this system is shown in Fig. 2. A double open-ended PVC pipe modeling the ear canal is suspended over a speaker via a hose clamp and ring stand. A membrane (exercise resistance band) is held in place by a separate hose clamp and stretched over one end of the pipe with constant tension. Delicately glued on the resistance band is a small circular mirror[9] effectively making it a mass loaded membrane.[10] The apparatus is placed equidistant between a screen and a laser pointer. The light ray from the laser is directed at the mirror and reflected on to a screen. The output of a function generator, which allows the user to control the amplitude and frequency of pressure waves originating from the speaker, is sent to an audio amplifier powering the speaker. The laser pattern seen on the screen is dependent on the mode[11] the speaker's pressure wave produces on the mass loaded membrane.

This system produces two circular membrane modes: Mode (0, 1) and Mode (1, 1). Mode (0, 1) contains one large anti-node at the center of the membrane effectively raising and lowering the mirror and never changing its orientation.[12] Therefore, the vertical height of the light reflection pattern on the screen is the membrane's range of motion. To increase the magnification of the range of motion, the mirror to screen horizontal distance can be increased.

Mode (1, 1) contains a nodal diameter with one circular node along the edge of the membrane.[13] This causes the mirror to change orientation in a "see-saw" like pattern, which changes the mirror's surface normal angle as shown in Fig. 4. When the mirror's surface normal angle changes, the direction of the light ray path also changes by that same angle. If the laser pattern is not vertical due to the see-saw effect of the mirror not aligning with the direction of the light ray path, the ear canal contains a slip union, making it rotatable to re-align the mirror. **Note:** There is no volume displacement in Mode (1, 1), likely causing little to no movement of the ossicles in a real ear, but for the purpose of this device as an educational tool any membrane movement is utilized to simulate hearing. The aforementioned modes are visualized in Fig. 3.

If the membrane produces Mode (0, 1), the user measures D, half the vertical height of the light reflection pattern, to obtain the membrane amplitude. For Mode (1, 1) the user measures D, and uses system constants (shown in Table I) and Eq. (1)[14] to calculate A_{approx}. A_{approx} corresponds to the height the mirror rises above its center while experiencing Mode (1,1) and is roughly proportional to the membrane amplitude. The user only measures half the vertical height because in both modes the range of membrane motion is double the membrane amplitude.

$$A_{approx} = \frac{1}{4}\left(\frac{mD\tan\theta}{H\sec^2\theta - D}\right). \tag{1}$$

Since m, θ, and H are held constant, Eq. (1) simplifies, using Table I constants, to

$$A_{approx} = \frac{2.16\,D}{112 - D}. \tag{2}$$

The largest D measured was never as large as 112 cm, making Eq. (2) continuous for the range of our D values. This equation should be used with introductory students so they are not put off by the intimidating look of Eq. (1). The given system constants in Table I were chosen to yield D values that

Table I. Physical properties of the electro-optical eardrum and several system constants.

Properties	Electro-Optical Membrane
Radius (cm)	5.8
Mass Density (g/cm^2)	0.020
Thickness (cm)	0.011

Electro-Optical Eardrum System Constants	
Mirror to Screen Horizontal Length, L (cm)	100
Height to Center of Laser Pattern, H (cm)	28
Angle of Laser, θ (deg)	60
Diameter of Mirror, m (cm)	5

range from 1.0-20 cm, which correspond to membrane amplitudes of 0.5-6.5 mm. The derivation of Eq. (1) uses only the law of reflection, geometry, and basic trigonometry.

Experimental procedure

An individual's hearing sensitivity can be determined by a simple test. First, a reference tone at a specific frequency and loudness level is chosen. Next, the frequency is changed from the reference but loudness level is kept constant. The individual then relays if the new sound is perceived as of equal, higher, or lower loudness than the reference tone. If the loudness at this new frequency is not perceived equal, the loudness level is changed until the individual perceives the new frequency tone as the same loudness level as the reference. From this collected data, an individual's hearing sensitivity can be plotted on a graph of frequency versus equal loudness. The graph displays the individual's perceived equal loudness contours of different frequencies.[15]

This system gives a person the ability to create a simple plot of hearing sensitivity. The first step is to determine a fixed membrane amplitude value, a.k.a., "reference tone." A membrane amplitude value of 1.0 mm, which corresponds to a D of 2.5 cm or laser pattern total height of 5.0 cm, was used in the original experiment. The user determines the lowest frequency the membrane responds to with this predetermined amplitude while at maximum power. Next, the user increases frequency (5-Hz increments suggested) and changes speaker power ("loudness level") until the device responds with the same predetermined amplitude. This process is repeated for the entire frequency range of the device whilst recording frequency and speaker power. These steps to determine the eardrum's range of hearing simulates playing tones of equal loudness to determine a person's range of hearing.[16]

The lowest speaker power recorded is used as a reference value for the calculation of a renormalized sound pressure level (SPL) data set. The power values are renormalized based on the sound frequency to which the membrane responds with minimum effort (minimum power).[17] To renormalize the data, simply divide all of the power values by the lowest speaker power value. To obtain the plot of hearing sensitivity, the user plots the renormalized SPL data set versus the frequency data set. Figure 5 shows a sample hearing sensitivity plot produced by the system, which is an analog to a human being's hearing sensitivity. The connecting line does not represent any specific fit of the data. The data point representing the lowest speaker power is shown as the blue diamond.

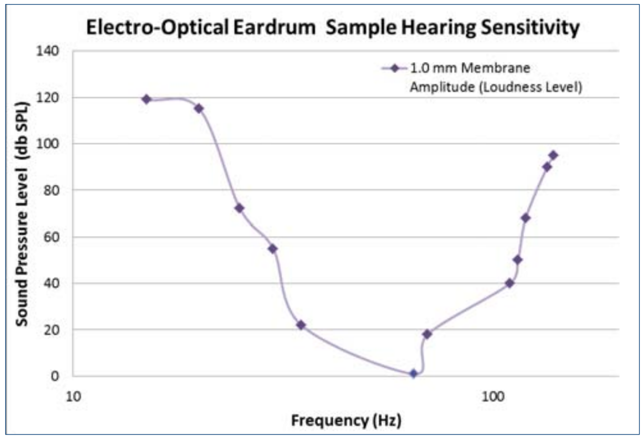


Fig. 5. Sample electro-optical eardrum hearing sensitivity plot.

Future work and unintentional outcomes

The system's initial design attached the PVC pipe with taut resistance band directly to a speaker. The direct contact and subsequent direct transfer of energy from the speaker produced several more modes on the membrane. Also, it produced an interesting phenomenon, coined "periodic mode switching." At fixed time intervals, the membrane spontaneously alternated between two modes of oscillation. It was hypothesized a thermal hysteresis effect was the cause; however, no further inquiry was made into this idea. There are several videos of this phenomenon available online.[18]

The system's final design suspends the PVC pipe over the speaker. With this suspended position, fewer modes are observed than the initial direct-contact system. Since the sheer weight of the mirror is the likely culprit for dampening or preventing the formation of higher membrane modes, future inquiries are suggested to use a circular mirror of less mass to view more modes or possibly silver paint for reflection. Other intriguing studies are the effects of different pipe diameters, mirror masses, and membrane tensions on the device's frequency range.

System demonstration

After completion, the system was demonstrated to its target audience. A student and I traveled to the Western Pennsylvania School for the Deaf (WPSD) in Pittsburgh, PA, to showcase the electro-optical eardrum to a high school physics class. For the trip, I added a special enhancement to the system: a microphone. In addition to demonstrating the device with the function generator supplying signal, I connected the microphone to the audio amplifier. At first I simply played music on a speaker, placed the microphone next to the speaker, and demonstrated the eardrum's response. Then, one of the deaf students asked to speak into the microphone. I handed over the microphone and was astonished at the pure excitement on his face as the eardrum responded to the speech. I came to realize the laser's reflection on the screen was one of the few times his speech was perceived by other deaf people or even by himself. It was an amazing moment.

Conclusion

The students at the high school were impressed with the system but also surprised. Shocking to me, they were surprised a hearing person took an interest in accommodating deaf students. After telling them about my friend Jay growing up, they understood my interest completely.

Jay went on to graduate from RIT and now has a great job; he handled his deafness without ever letting it become an issue. However, for some students a disability is something not easily set aside. How can a blind student investigate the images produced by thin lenses? How can a student construct simple resistor circuits with a spinal cord injury limiting kinesthetic ability? And ultimately, can educators realistically design accommodations for every type of student who walks into their classroom? The answer to this last question is, unfortunately, no—but we can sure try.

Since the demonstration at the deaf school, I have been motivated to discover additional adaptations to laboratory exercises to ensure they can accommodate the broadest audience possible. The goal of this article is not to simply showcase a new device, but also to inspire in others the same enthusiasm for classroom accommodation. As a science educator you really must be an innovator. Thus, as your peer, there is one last question I must ask you: Are you prepared to educate whomever walks into your classroom?

Acknowledgments

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