Visualizing Sound with an Electro-Optical Eardrum

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INTRODUCTION

An introductory physics laboratory experiment 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.

However, students with disabilities such as deafness would not be able to participate in all aspects of this investigation. Accommodations must be made in university educational settings to ensure *all* students have the proper tools to investigate scientific phenomenon and learn.

OBJECTIVES

1) To create a physics lab accommodation allowing a deaf student to determine the hearing sensitivity of an electro-optical eardrum.

2) To simulate playing tones of equal loudness to determine a person's range of hearing by determining the eardrum's range of hearing.

BIOPHYSICS OF HEARING

The purpose of the auditory system is to convert sound (pressure) waves into electrical signals the brain can interpret.

1) A sound wave travels down the auditory canal

2) The sound wave reaches the eardrum (tympanic membrane) at the end of the canal and oscillates it inward and outward

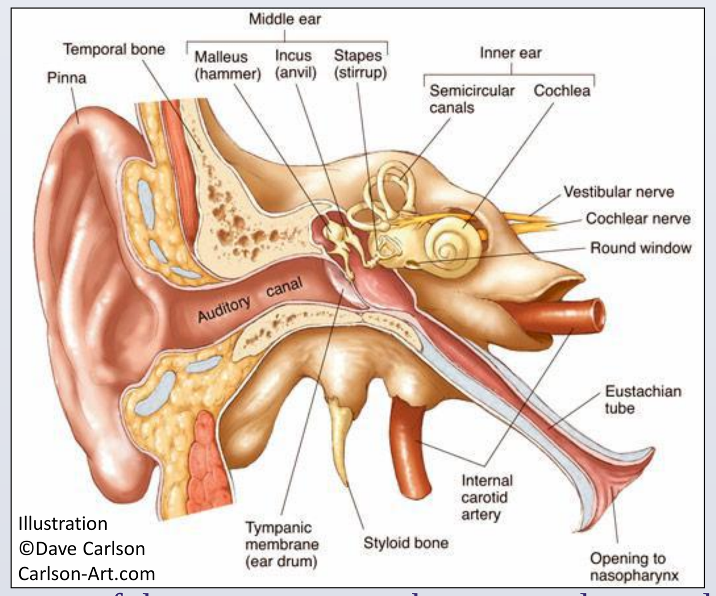
3) The eardrum oscillation vibrates the 3 inner ear bones (malleus, incus, stapes)

4) The vibration of the stapes strikes the stapes faceplate which rests against the cochlea, a fluid-filled tube with thousands of hair-like cells

5) This strike sends a compression wave through the cochlea

6) If the frequency of this wave matches the resonant frequency of the hair cells, it will cause them to resonate and vibrate with larger amplitude

7) The large amplitude movement initiates nerve cells to emit electrical impulses to the brain



When one or more of these steps cannot be executed correctly, deafness occurs. There are two types of deafness: conductive and sensorineural. Conductive deafness occurs when sound waves cannot enter the inner ear, usually due to physical impedance. Sensorineural deafness most commonly involves damaged hair cells, auditory nerves, or auditory processing in the brain.

HEARING SENSITIVITY

An individual's hearing sensitivity can be determined by a simple test….

…..chose a reference tone at a specific frequency and loudness level

…..change the frequency from the reference but keep loudness level constant

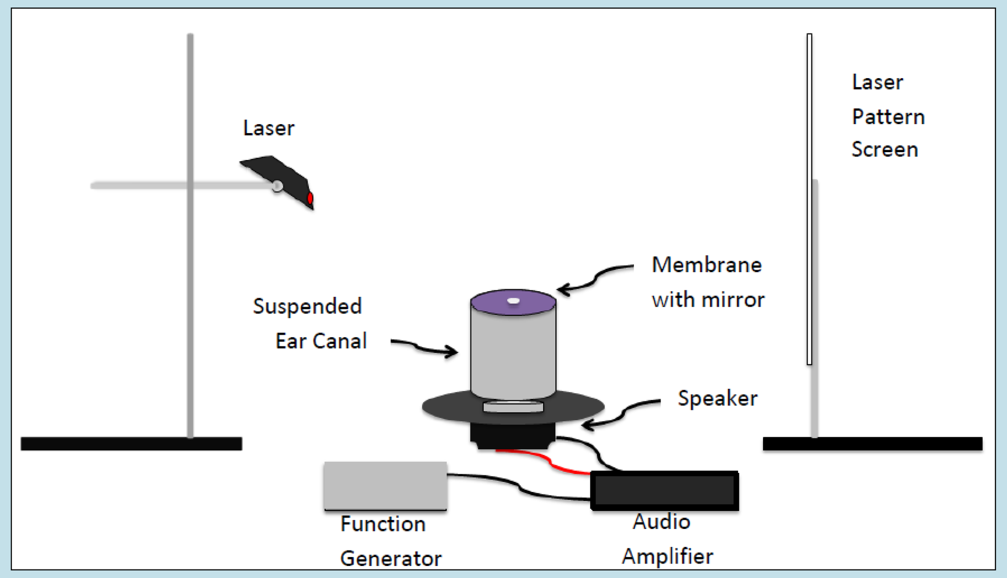
…..The individual then relays if the new sound is perceived as of equal, higher, or lower loudness than the reference tone.

…..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 vs. equal loudness. The graph displays the individual's perceived equal loudness contours of different frequencies

EXPERIMENTAL SET UP

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 effectively making it a mass loaded membrane. 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 that the speaker's pressure wave produces on the mass loaded membrane.



PROCEDURE

- Determine a "reference tone" - fixed membrane amplitude
- Use the membrane amplitude equations to determine the membrane amplitude utilizing the laser reflection pattern
- Determine lowest frequency the membrane responds to with this amplitude while at max power
- Increase frequency by 5 Hz increments, adjusting speaker power, aka "loudness level" each time so the membrane responds with the predetermine reference amplitude
- Re-normalize data and use to generate a hearing sensitivity plot

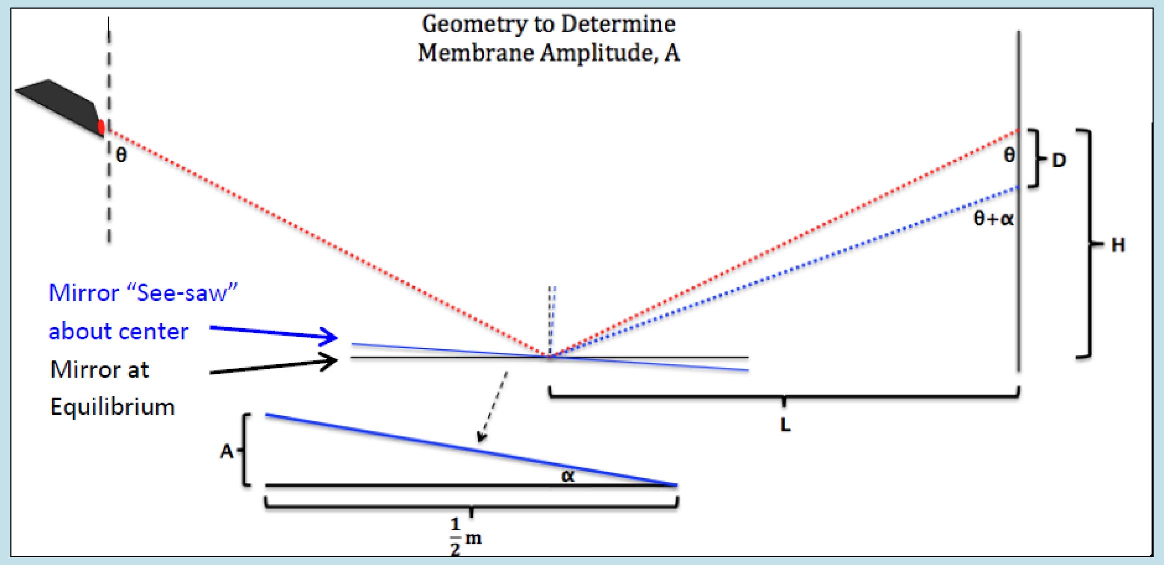
Properties	Electro-Optical Membrane
Radius (cm)	5.8
Mass Density (g/cm^2)	0.020
Thickness (cm)	0.011

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

THE EARDRUM SYSTEM

- This system produces two circular membrane modes:
  1) Mode (0, 1)- one large anti-node at the center of the membrane effectively raising and lowering the mirror and never changing its orientation
  2) Mode (1, 1)- one circular node along edge of membrane, one anti-node at the center, causing the mirror to change its orientation in a "see-saw" pattern
- Membrane amplitude is found from the laser reflection pattern
  - Mode (0, 1): A= half the vertical height of the laser reflection pattern
  - Mode (1,1): $A = \frac{1}{2}\left(\frac{mD\tan\theta}{H\sec^2\theta - D}\right)$

    where D is half the vertical height of the reflection pattern

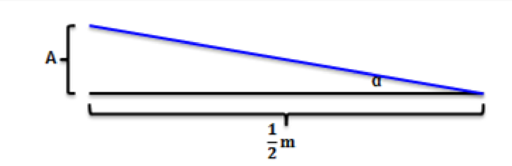


MATHEMATICS FOR MODE (1,1) MEMBRANE AMPLITUDE

Derivation of Amplitude equation for Mode (1,1) via the following geometry

$$\tan\alpha = \frac{A}{\frac{1}{2}m}$$

$$\tan\alpha = \frac{2A}{m}$$



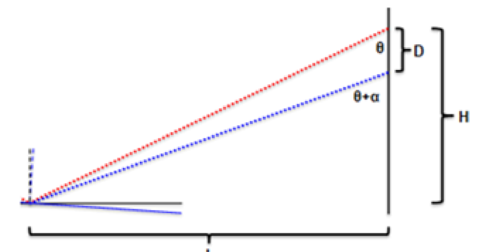
$$\tan\theta = \frac{L}{H}$$

$$\tan(\theta+\alpha) = \frac{L}{H-D}$$

$$(H-D)\tan(\theta+\alpha) = H\tan\theta$$

$$(H-D)\left(\frac{\tan\theta+\tan\alpha}{1-\tan\alpha\tan\theta}\right) = H\tan\theta$$

$$(H-D)\left(\frac{\tan\theta+\frac{2A}{m}}{1-\frac{2A}{m}\tan\theta}\right) = H\tan\theta$$



$$\left(\frac{(H-D)\tan\theta+\frac{2A}{m}(H-D)}{1-\frac{2A}{m}\tan\theta}\right) = H\tan\theta$$

$$(H-D)\tan\theta+\frac{2A}{m}(H-D) = H\tan\theta-\frac{2A}{m}H\tan^2\theta$$

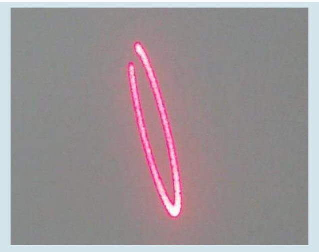
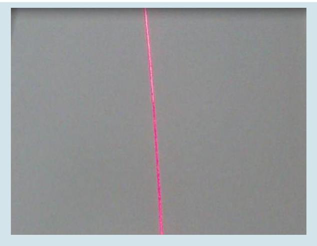
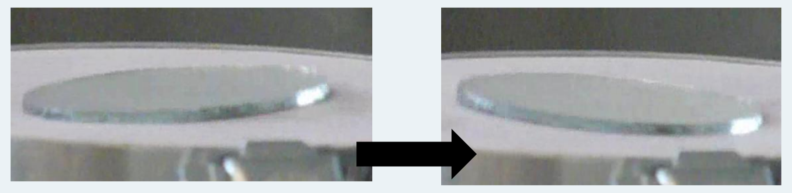
$$\frac{2A}{m}(H-D)+\frac{2A}{m}H\tan^2\theta = H\tan\theta-(H-D)\tan\theta$$

$$\frac{2A}{m}(H+H\tan^2\theta-D) = D\tan\theta$$

$$\frac{2A}{m} = \frac{D\tan\theta}{(H+H\tan^2\theta-D)}$$

$$A = \frac{1}{2}\left(\frac{mD\tan\theta}{H\sec^2\theta-D}\right)$$

SOUND VISUALIZATION

	Mode (0,1)	Mode (1,1) – "Seesaw"
Laser Pattern		
Mirror Pattern		

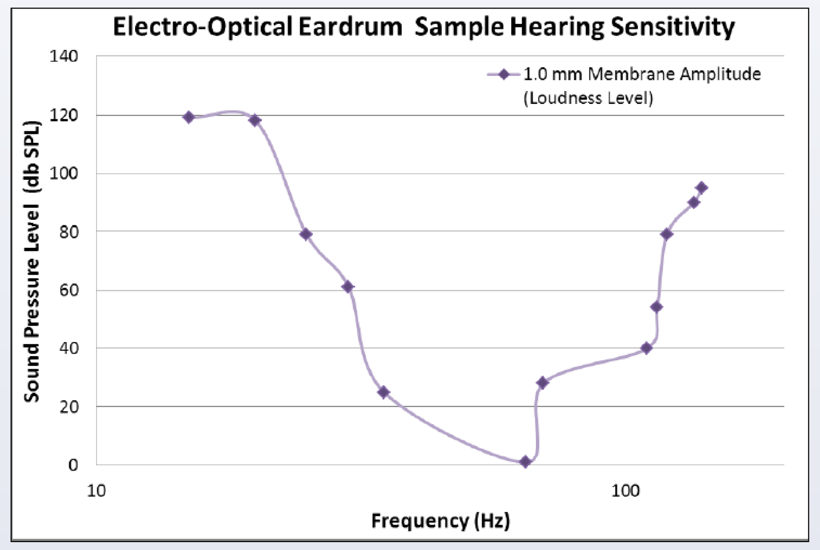
FUTURE WORK

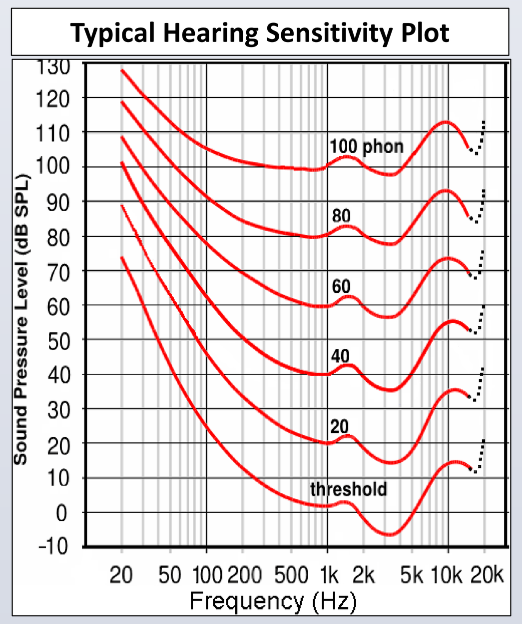
The system's initial design attached the PVC pipe with taut resistance band directly to a speaker. The direct contact and subsequent direct transfer of energy from the speaker produced several more modes on the membrane than the final suspended PVC pipe position. Since the sheer weight of the mirror 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.

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.

Other intriguing studies are the effects of different pipe diameters, mirror masses, and membrane tensions on the device's frequency range.

DATA TABLES AND PLOTS





Electro-Optical Tympanic Membrane Data		*Physical Properties*	Membrane Radius, r (cm)	Mass Density, μ (g/cm^2)	Thickness (mm)	
			5.75	0.02	0.11	
Horizontal Length from Pattern to Mirror (m)			1		Typical Human Ear Drum Properties	
Height, H (m)			0.28		Radius (cm)	0.32
Laser Angle, θ (deg)			60		Mass density (g/cm^2)	0.04
Mirror Length, m (cm)			5		Thickness (mm)	0.70
Sample Data Point						
Frequency (Hz)	Speaker Voltage (V)	Speaker Current (A)	**Speaker Power (W)**	**Sound Pressure (dB)**	Laser Displacement (cm)	**Mirror Amplitude A (mm)**
65	2.4	0.16	**0.192**	**22.1**	6.67	**2.74**

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3. National Health Services- Choices, "Hearing Impairment (Deafness) – Causes," (Feb 2011); http://www.nhs.uk/Conditions/Hearing-impairment/Pages/Introduction.aspx (Heading "How Hearing Works")

4. National Health Services- Choices, "Hearing Impairment (Deafness) – Causes," (Feb 2011); http://www.nhs.uk/Conditions/Hearing-impairment/Pages/Causes.aspx (Headings "Conductive and Sensorineural Hearing Loss")

5. Use of mirrors on human eardrums to detect amplitude of motion, http://audilab.bmed.mcgill.ca/AudiLab/ear.html (Retrieved 03/11/2013)

6. This device is original but the concept of placing an elastic material over an open ended object was read about years ago on a website that is no longer in existence. http://scied.unl.edu/pages/mamres/pages/demos/denver/eardrums.html

7. Daniel A. Russell, *"Vibrational Modes of a Circular Membrane"* http://www.acs.psu.edu/drussell/demos/membranecircle/circle.html Copyright 2004-2011

8. Wolfe, John, "Hearing test on-line: sensitivity, equal loudness contours and audiometry"; http://www.phys.unsw.edu.au/jw/hearing.html

9. George Mather, *Foundations of Perception*, 1st ed. (Psychology Press Ltd., 2006), pp. 118

10. Videos found at YouTube channel http://www.youtube.com/user/TheTruncale?feature=mhee