CHAPTER 1

INTRODUCTION

1.1 Motivation

1.1.1 Noise induced hearing loss

Noised induced hearing loss is hearing loss as a result of exposure to harmful noise. This harmful noise can be either impulse sounds like explosions or long duration exposure such as that experienced on the deck of an aircraft carrier. As a result of this exposure, the hair cells in the cochlea are damaged and cannot be repaired [1]. The Occupational Safety and Health Administration (OSHA) standard 29 CFR 1926.52(d)(1) specifies the permissible noise exposures as a function of the duration of the exposure. The values from this standard are shown in Table 1.1. OSHA standard 29 CFR 1926.52(e) also specifies that exposure to impulse or impact noise should not exceed 140 dB peak SPL.

Table 1.1: OSHA Standard for Permissible Noise Exposures.

Duration Per Day (hours)	Sound Level (dBA slow response)
8	90
6	92
4	95
3	97
2	100
1 1/2	102
1	105
1/2	110
1/4 or less	115

1.1.2 Current hearing protection devices (HPDs)

The majority of HPDs used today can be broken down into two categories: passive and active. Passive devices such as earplugs and earmuffs reduce the sound level reaching the inner ear by blocking the air conduction pathways. Active noise reduction (ANR) devices use noise canceling circuitry and transducers to add an out-of-phase version of the noise so that when summed the noise is cancelled out [2].

Failures of current HPDs

Multiple factors contribute to reduce the effectiveness of passive HPDs when used in the real world. Air leaks between an earplug and the pinna can reduce the attenuation by 5 to 15 dB. Vibration of the HPD can also reduce the attenuation of the device. This occurs in earplugs due to the flexibility of the ear canal which can cause the earplug to vibrate like a piston. This also occurs with earmuffs due the mass-spring system of the earmuff headband and the earmuff cushions. As a result of vibration, the attenuation limit for earmuffs and earplugs at 125 Hz becomes 25 dB and 40 dB, respectively. A less common reduction in attenuation is due to transmission through the material of the HPD. This reduction is most noticeable when using materials with lower attenuation and for earmuffs at certain frequencies. The final factor contributing to the reduced effectiveness of HPDs is bone conduction. Current HPDs are designed to attenuate sound transmission via the air conduction pathways but not the bone conduction pathways. For certain frequencies, bone conduction may become the dominant pathway, thus reducing the effectiveness of the HPD [3].

ANR devices appear to be a promising technology, but devices available today are unable to achieve the performance of passive devices. Earmuffs with ANR added have been shown to improve real-ear attenuation compared to earmuffs or earplugs used by themselves at low frequencies, but the combination of earplugs and earmuffs has better attenuation than the earmuffs with ANR [2].

Crews on aircraft carrier flight decks can be subjected to noise levels as high as 150 dB. Due to limits in attenuation achievable by current HPDs, it is still possible for noise induced hearing loss to occur even when wearing earplugs and earmuffs due to bone conduction [3, 4]. The goal of this project is to determine the dominant bone conduction pathways. Once these pathways have been determined it may be possible to design HPDs that reduce the sound propagated through them.

1.2 Methods

1.2.1 Finite element analysis (FEA)

The human head is a complex scatterer composed of multiple layers and has a complex geometry. As a result of this, analytic solutions to sound scattering do not exist and a numerical method must be used. The finite element method (FEM) was chosen for this project. The finite element method can compute the approximate solution to scattering from an arbitrary geometry with multiple layers. The idea behind FEM is to divide the continuous volume into a finite number of discrete volumes, called elements. Each of these elements has properties associated with it such as sound speed and density. Each of these elements will have a series of nodes associated with it, each having a position in space associated with it. FEM then uses the equations governing acoustic wave propagation to compute the pressure at these nodes. The pressure between nodes can also be approximated by interpolating the pressure of the surrounding nodes.

The finite element method has other advantages besides the ability to simulate arbitrary volumes. It can also be used to compute solutions to numerous sources such as plane waves and point sources. Both time-harmonic and transient problems can be solved using the finite element method as well.

The finite element method does have some drawbacks, though. The solution step of the finite element procedure requires solving a system of N equations, where N is the number of nodes. In general, as the number of nodes is increased the accuracy of the solution increases. A tradeoff exists between computational efficiency and accuracy. For transient analysis, error can also be introduced if the time step is chosen too large. In general, as the time step decreases, the accuracy increases but requires more computation.

1.2.2 Ray tracing

One method of visualizing the propagation of acoustic energy is ray tracing. Ray tracing is often used in geometrical acoustics when the size of the scatterer is much larger than a wavelength. If this is the case, the full wave equation does not need to be solved and the simpler Eikonal equation is used instead. In doing so, the problem is solved in terms of the propagation of rays instead of waves. For the case of plane wave incidence, a uniform grid of rays normal to the wavefront at time $t = 0$ is drawn. As the wave propagates, these rays are bent according to the Eikonal equation and thus the wave is propagated. If the intensity at time $t = 0$ is I_0 and the density of rays passing through an area at this time is N_0 rays/m^2, and if the density of rays at a time $t = \tau$ is N_1, then the intensity is $N_1 I_0 / N_0$. Thus the areas with high concentrations of rays intersecting the wavefront have a higher intensity [5]. By finding the points with the highest ray density, we can determine the dominant pathways through which sound travels to reach the cochlea.

For the case of the human head, the wavelength is on the order of the size of the human head for audible frequencies. As a result, the small wavelength assumption required for use of the Eikonal equation does not apply to the current problem and the full wave equation must be solved. Even though the Eikonal equation cannot be used, ray tracing can still be performed in the following way. Start with a uniform grid of rays normal to the wavefront at time $t = 0$. Find the intersection of these rays with the wavefront at some small time increment, dt. Next compute the normal to the wavefront at time $t = dt$ at the intersection points. Compute the intersection of these normals with the wavefront at time $t = 2dt$. These two steps are repeated until the end of the domain is reached. The result will be a set of ray paths that can be interpreted in the same way as those computed using the Eikonal equation.