

A Simplified Solid Mechanical and Acoustic Model for Human Middle Ear

Adarsh Venkataraman Ganesan, Sundaram Swaminathan, and Rama Jayaraj

Abstract—Human middle-ear is the key component of the auditory system. Its function is to transfer the sound waves through the ear canal to provide sufficient stimulus to the fluids of the inner ear. Degradation of the ossicles that transmit these sound waves from the eardrum to the inner ear leads to hearing loss. This problem can be overcome by replacing one or more of these ossicles by middle-ear prosthesis. Designing such prosthesis requires a comprehensive knowledge of the biomechanics of the middle-ear. There are many finite element modeling approaches developed to understand the biomechanics of the middle ear. The available models in the literature, involve high computation time. In this paper, we propose a simplified model which provides a reasonably accurate result with much less computational time. Simulation results indicate a maximum sound pressure gain of 10 dB at 5500 Hz.

Keywords—Ear, Ossicles, COMSOL, Stapes.

I. INTRODUCTION

HEARING is a branch of science concerned with the physiology of sound, perception and relates with the field of processing and interpreting the sound signals and their disorders. Hearing is the second most important sensible part that will make more perception and awareness with other people [1]. Human ear has the ability of detecting minute variations of the surrounding pressure. The ear is responsible for translating variations in air pressure whether from speech, music or other sources [2] into neural activity for our perception and interpretation of sound. The ear can be divided into main sections such as outer ear, middle ear and inner ear. Each part performs a specific function in processing sound information. Outer and middle parts of the ear are directly functioning with atmospheric pressure. These two parts are the conducting domain from the atmosphere. In human, the sound waves funnel into the middle ear via the external ear canal. The effect of compression and rarefaction of the sound wave create a longitudinal wave motion at the beginning of the middle ear. The vibration of the sound is amplified and converted into a displacement in the middle ear. This displacement energy is enough to make the movement into the fluid in the cochlea. Depending upon the fluid movement, a

particular receptor cell is activated to produce an electric potential (mV) which is transferred to the brain through the auditory nerve, to decode into the original message signal.

Bance et al. [3] studied the impact of size of incus prosthesis head on tympanic membrane vibration. Voss and Peake [4] studied the relationship between sound transmission and perforation using the finite element method. Dai et al. [5] studied the combined effects of fluid and air in middle ear cavity. Wen et al. [6] optimized the design of the cartilage myringoplasty using finite element analysis. Tenney et al. [7] studied the restoration of hearing of stapes prosthesis in the short term and the impact of angle of implantation on hearing. Yao et al. [8] designed a numerical model on sound- solid coupling in the human ear. The above studies have promoted the development of the biomechanics of the middle ear.

However, these preliminary studies have all used highly complicated finite element models, which involve high computation time. In this paper, we have designed a simplified model for the human ear that involves less computation time. The middle ear is modeled as lever system by using COMSOL Multiphysics. COMSOL is an effective software tool to analyze the acoustics characteristics and to perform solid mechanical calculations.

II. BUILDING A SIMPLIFIED MODEL

The FE modeling approach was divided into three parts: computer-aided geometric modeling, constructing the working FE model, and cross-calibration of the working model to obtain the final FE model.

A. Geometric Modeling

The morphology of a normal fresh human temporal bone (female, age 52, right ear) was taken as the reference for building a simplified FE Model. Here, we have built the human ear model with a series of beams. The FEM build-up of each functional element of the human middle ear is mentioned below.

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TABLE I
 MECHANICAL AND GEOMETRIC PROPERTIES OF EAR DRUM

| Properties | Range (right ear) | Our Values |
|--|---|---------------------|
| Density (kg/m ³) | 1.2x10 ³ [9] | 1.2x10 ³ |
| Young's modulus (N/m ²) | pars tensa [10]: 2.0x10 ⁷ (circumferential), 3.2x10 ⁷ (radial) pars flaccida [11]: 1.0x10 ⁷ (circumferential), 1.0x10 ⁷ (radial) | 3.5x10 ⁷ |
| Diameter along the manubrium (mm) | 8.80-9.68 [12] | 9.092 |
| Diameter perpendicular to the manubrium (mm) | 8.80-9.20 [12] | |
| Height of the cone (mm) | 1.35-1.55 [12] | |
| Surface area (mm ²) | 61.41-67.86 [12] | 64.89 |
| Thickness (mm) | 0.39-0.49 [12] | 0.44 |

TABLE II
 MECHANICAL AND GEOMETRIC PROPERTIES OF MALLEUS

| Properties | Range (right ear) | Our Values |
|--|--|-----------------------|
| Density (kg/m ³) | 2.55x10 ³ (for head), 4.53x10 ³ (for neck), 3.70x10 ³ (for handle) [13] | 1.2x10 ³ |
| Young's modulus (N/m ²) | 1.41x10 ¹⁰ [14] | 1.41x10 ¹⁰ |
| Length from the manubrium to the end of the lateral process (mm) | 4.18-4.41 [12] | 4 |
| Length from the lateral process to the end of the head (mm) | 4.41-5.2 [12] | 4.48 |
| Total height (mm) | 7.54-8.12 [12] | 7.08 |

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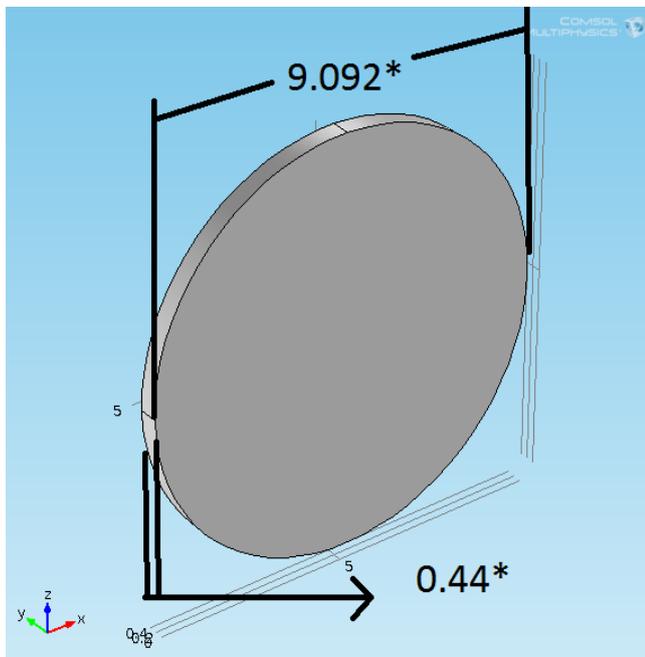


Fig. 1 Model of Ear Drum

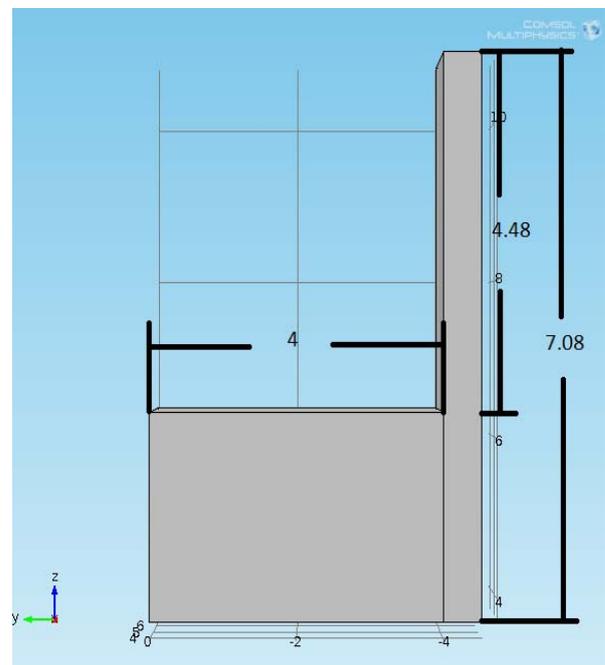


Fig. 2 Model of Malleus

Figs. 1 and 2 show the model of Ear Drum and Malleus respectively.

TABLE III
 MECHANICAL AND GEOMETRIC PROPERTIES OF INCUS

| Properties | Range (right ear) | Our Values |
|--|---|-----------------------|
| Density (kg/m ³) | 2.36x10 ³ (for body), 2.26x10 ³ (for short process), 5.08x10 ³ (for long process) [13] | 1.2x10 ³ |
| Young's modulus (N/m ²) | 1.41x10 ¹⁰ [14] | 1.41x10 ¹⁰ |
| Length along the long process (mm) | 6.36-6.71 [12] | 6.51 |
| Length along the short process (mm) | 3.97-4.33 [12] | 3.63 |

TABLE IV
 MECHANICAL AND GEOMETRIC PROPERTIES OF STAPES

| Properties | Range (right ear) | Our Values |
|--|----------------------------|---------------------|
| Density (kg/m ³) | 2.20x10 ³ [13] | 1.2x10 ³ |
| Young's modulus (N/m ²) | 1.41x10 ¹⁰ [15] | |
| Height (mm) | 2.84-3.19 [12] | 2.87 |
| Length of the footplate (mm) | 1.99-2.52 [12] | 2.34 |
| Width of the footplate (mm) | 0.91-1.38 [12] | 1.33 |
| Thickness of the footplate (mm) | 0.91-1.25 [12] | |

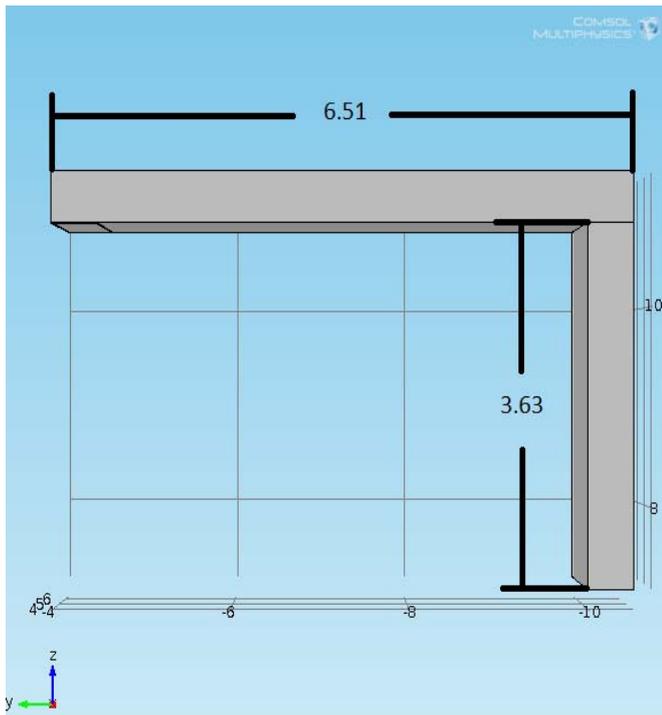


Fig. 3 Model of Incus

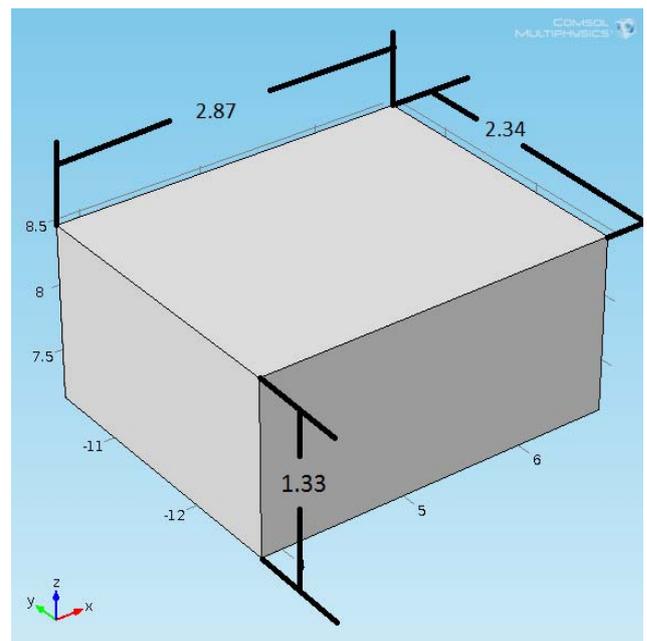


Fig. 4 Model of Stapes

Figs. 3 and 4 show the model of Incus and Stapes respectively

B. Boundary Conditions

Because of the sensitivity of displacement of microstructure to the dynamical response of ear structure, the connection between malleus and incus was regarded as fixed constraint, which is to say its displacement in all three orthogonal directions is zero. The defined boundary condition is listed below.

1. 90 dB SPL (i.e.,) 0.632Pa, from 20Hz to 20000Hz, was set on the opening surface of external auditory canal.
2. The displacement of connection between soft tissues and temporal bone was defined to be zero in three orthogonal directions.
3. The displacement of outer edge of tympanic membrane was defined to be zero in three orthogonal directions.

III. RESULTS

The above model was used to impose sound incentive on external auditory canal. Fig. 5 shows that when the range of frequency is between 5 and 6 kHz, the effect that imposes sound incentive on external auditory canal is higher than that of Eardrum with an increase of 10 dB. The increase reaches the maximum when the frequency is 5500Hz. This result can be explained by the physical principle that inflatable pipe closed at one end can generate resonant interaction with the acoustic whose wavelength is 4 times tube length. The external auditory canal belongs to this type tube _one end opening, the other end terminated at the tympanic membrane and its length is about 1.5-1.7 cm; therefore, external auditory canal plays a role of amplification in signals among the range of 5000–6000Hz frequency.

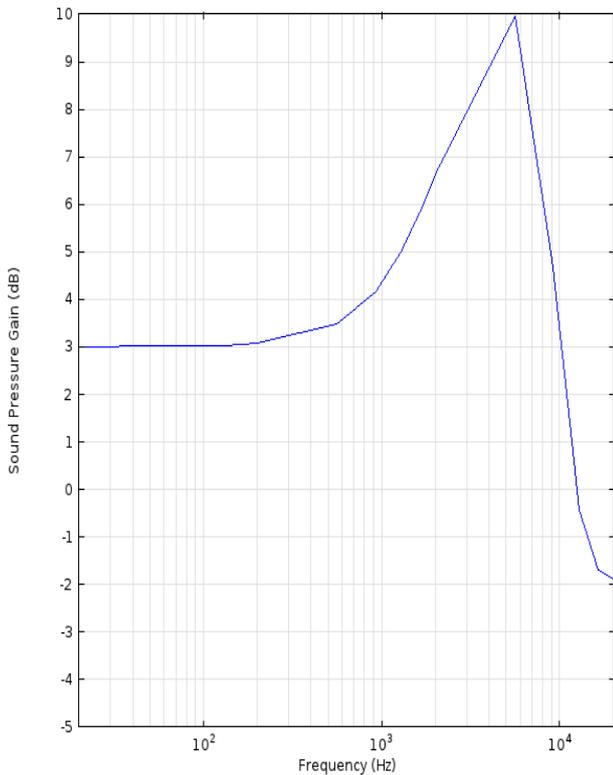


Fig. 5 Sound Pressure Gain vs. Frequency

Fig. 6 shows the acoustic pressure distribution across the middle ear.

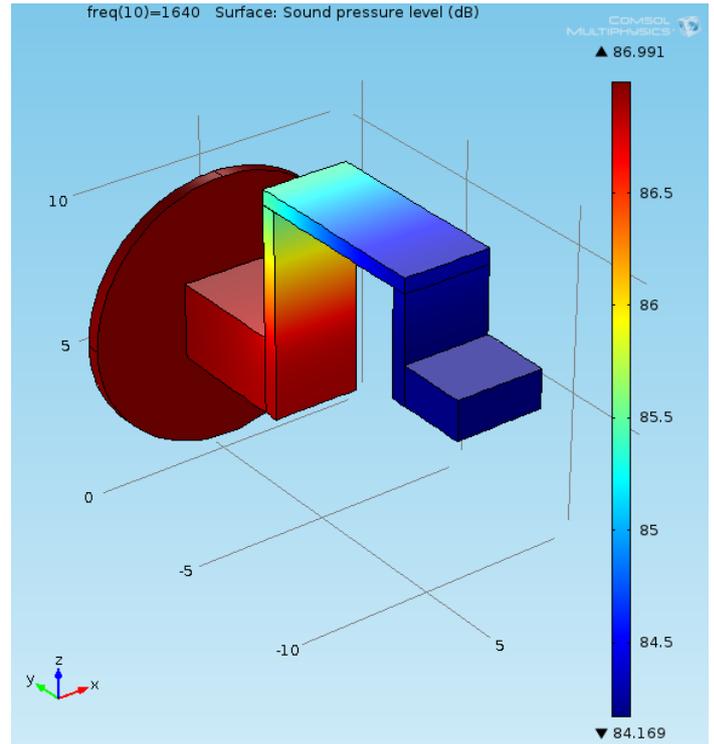


Fig. 6 Sound Pressure Level distribution

The solid mechanical problem was also solved for the applied acoustic pressure. Fig. 7 shows the total displacement of the middle ear at different positions.

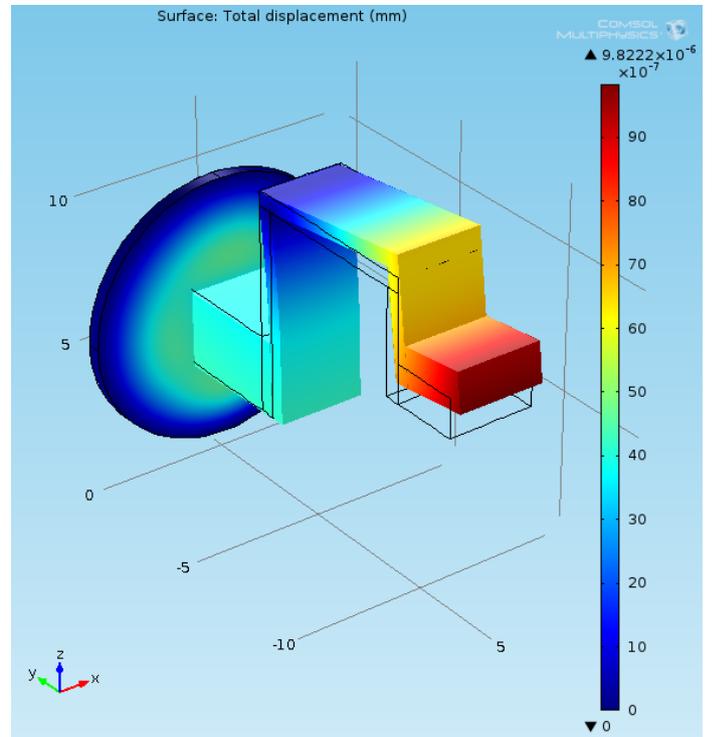


Fig. 7 Total displacement for the sound pressure level of 90 dB

IV. CONCLUSION

We have constructed an FE model of the human middle ear based on histological data. The paper achieves the following conclusions by simulation

1. A simplified finite element model of middle ear and made use of this model to do the frequency response analysis.
2. The calculation results showed that maximum pressure gain of 10 dB, occur at 5500 Hz.
3. The total displacement at the footplate of the stapes is 9.8222×10^{-6} mm and at the umbo is 4.55×10^{-6} mm.

The results obtained are almost synchronous with the results available in the literature. However, the improvements in the model are necessary in the future studies. This will enhance the potential for physiological and pathological applications of the model, for instance, simulating acoustic effects of otitis media and other defects on transmission of the sound in the middle ear to the cochlea.

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