Homework 2: Middle-Ear Simulation Extension

Mike Lundy - MUE 610

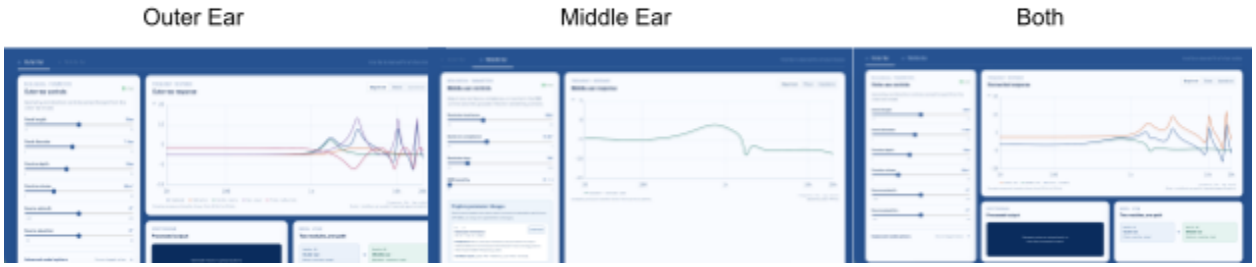
Website Link: https://interactive-ear-modeling.vercel.app/

Github Link: https://github.com/mml260/Interactive-Ear-Modeling

Objective and Model Scope

This portion of the build extends upon the outer ear simulator with a standalone web application model. The signal path of the model goes from the pinna and concha, to the ear canal, the eardrum, ossicles, and ends with the cochlear load. The app displays and provides real time audio playback for the outer ear, middle ear, and both of them combined. Bascading between the outer ear model and inner ear model is connected as a multiplication of their transfer functions (H_total(f) = H_outer(f) × H_middle(f)) but doesn't account for any loading between the stages.

Figure 1: Outer, middle, and combined magnitude responses in the web application.



Middle Ear Circuit Verification

The circuit representation of the middle ear that was provided was implemented as subsystems including Z_cavity, Z_eardrum, Z_ossicles, Z_joint, and Z_cochlea. The output transfer function is the pressure ratio from the input to the cochlear load. The impedances and subsequent transfer function are listed below.

```
Z_cavity = (Z_Cp + Z_La + Z_Ra) || Z_Rm || Z_Ct
Z_eardrum = Z_CD1 + (Z_LD || (Z_CD2 + Z_RD2)) + Z_RD1
Z_ossicles = Z_CO + Z_LO + Z_RO;  Z_load = Z_joint || Z_cochlea
Z_middle = Z_cavity + [Z_eardrum || (Z_ossicles + Z_load)]
H_middle = (Z_after_A / Z_middle) × (Z_load / (Z_ossicles + Z_load))
```

The function's validity was proved in code rather than comparing output graphs. At 1 kHz, the tests proved each branch from the impedance equations and compared the real and imaginary components of each subsystem. The tests additionally verified that the resistors impedance does not change as the frequency changes and that voltage and current stay in sync. As frequency goes up, the inductor's impedance goes up therefore blocking more current. The capacitor impedance goes down as frequency increases, allowing more current to flow and the current is 90 degrees out of phase with the voltage. 21 automated tests were run prior to the production build.

Component Values

The exact component values for the given circuit in Figure 2 were provided as shown.

Figure 2: Zwislocki style circuit diagram of middle ear

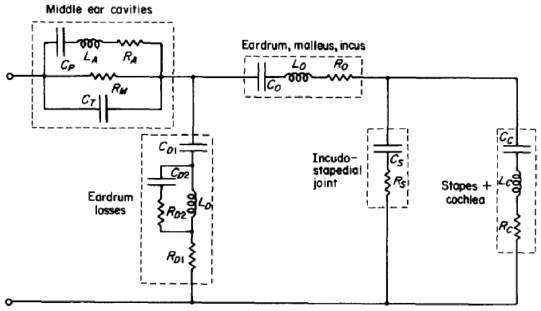


TABLE 1
Component values in electroacoustic analogues

Component	Value in final model (Figure 12)	Value used to obtain loci in Figure 8
L_A	14 mH	14 mH
L_O	40 mH	40 mH
L_D	15 mH	15 mH
L_C	45 mH	20 mH
R_M	390 Ω	390 Ω
R_O	70 Ω	70 Ω
R_{D1}	200 Ω	40 Ω
R_{D2}	12 Ω	220 Ω
R_{D3}	5900 Ω	—
R_A	10 Ω	10 Ω
R_C	550 Ω	600 Ω
R_S	3000 Ω	3000 Ω
C_P	5·1 μF	5·1 μF
C_T	0·35 μF	0·35 μF
C_O	1·4 μF	1·4 μF
C_{D1}	0·8 μF	0·23 μF
C_{D2}	0·4 μF	0·4 μF
C_{D3}	0·2 μF	—
C_S	0·25 μF	0·25 μF
C_C	0·65 μF	0·6 μF
C_{ST}	0·25 μF (near-maximal response) $-\infty$ (no response)	—

From Zwislocki's 1962 publication "Analysis of the Middle Ear Function. Part 1: Input Impedance" (https://www.yorku.ca/cberge/1410W2013/lnotes/Zwislocki1962.pdf), the cavity impedance and compliance was derived from the frequency response provided from figure 3 on page 1516 and the simplified malleus and ossicle circuit behavior is explained on page 1517. Baseline component values were taken from the table above. The cochlear inertance was set to zero as a documented model simplification.

Three AI-Assisted Experiments

Each case listed on the middle ear section of the model changes one perameter of the middle ear while resetting the other controls to the OME scenario. The predictions were made before running the model and are compared with the calculated ear response.

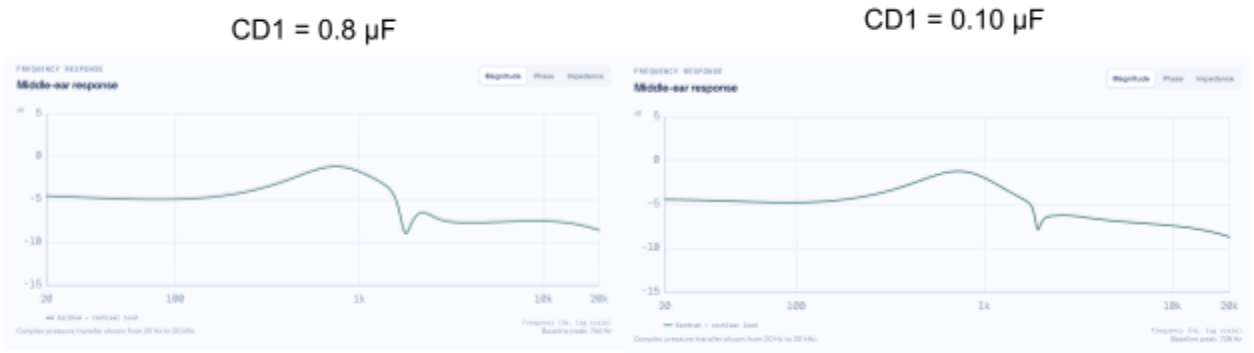
Experiment 1 - Ossicular Inertance
Controlled change: LO: 40 → 60 mH (+50%).
Pre run prediction: A 50% increase in inertance should attenuate high frequency after middle frequency peak.
Calculated result: Peak frequency moved 871 Hz to 752 Hz. Relative to baseline, the response changed −1.32 dB at 2 kHz and −2.00 dB at 4 kHz.
Comparison: The high movement of the low pass filter occurred as expected. However, it was noticed that there is a slight peak increase for the broad band frequency peak.

Figure 3: Inertance comparison



Experiment 2 - Eardrum Compliance
Controlled change: CD1: 0.8 → 0.10 μF
Pre run prediction: A higher capacitance should change the behavior of the broad peak by attenuating it.
Calculated result: Peak frequency moved from 745 Hz to 726 Hz and peak magnitude changed from −1.11 to −1.16 dB. The response at 1 kHz was −0.21 dB relative to baseline.
Comparison: The response moved downwards and was consistent with the prediction.

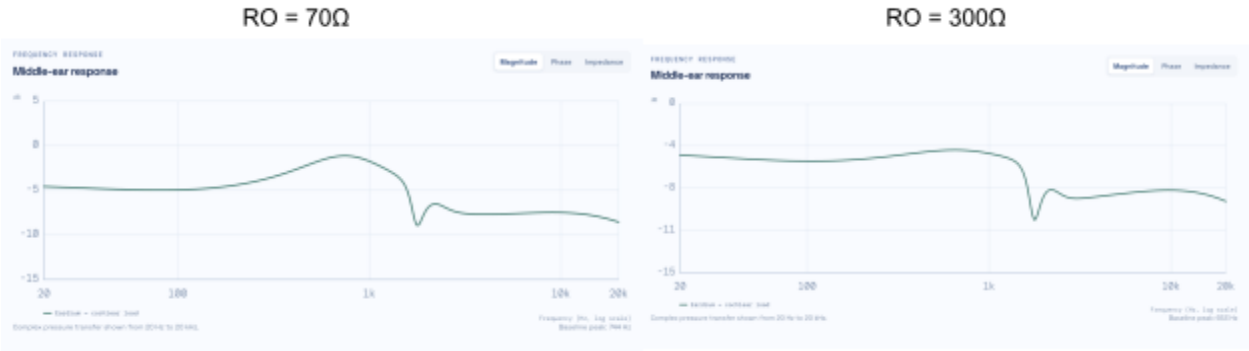
Figure 4: Compliance Comparison



Experiment 3 - Ossicular Loss
Controlled change: R0: 70 → 300 Ω
Pre run prediction: Higher resistance should cause more energy to dissipate which would reduce the amplitude of the broad peak

Calculated result: Peak frequency moved from 745 Hz to 649 Hz. The peak magnitude changed from −1.11 to −4.11 dB. The response at 1 kHz was −2.69 dB relative to baseline.
Comparison: As predicted, the larger the resistance, the peak lost significant magnitude.

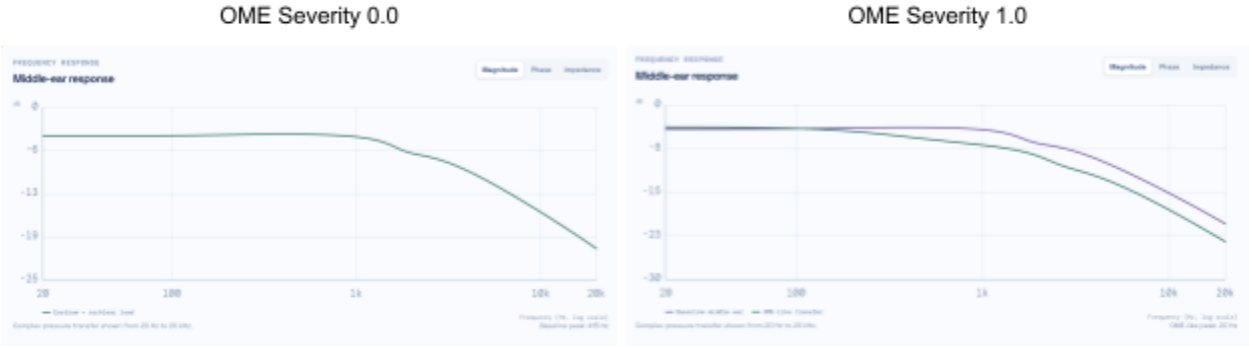
Figure 5: Loss Comparison



OME Transfer Scenario

The app includes a small child otitis media with effusion (OME) sensitivity scenario. Its continuous severity control reduces eardrum and joint compliance while increasing ossicular inertance and loss. When severity is above zero, the app overlays the baseline and OME responses and applies the same profile to playback.

Figure 6: Small child OME transfer comparison



AI Use and Engineering Log

For the circuit interpretation and original gathering of component values, I decided to use the verified topology that was provided in the notes instead of using AI to interpret alternative routes that aligned with the frequency response from the Zwislocki paper. As a result, this also confirmed that the values that were chosen retained a similar baseline rather than coming up with arbitrary values. However, the component values were later provided and reimplemented into the middle ear model. When building the app, the first custom FFT filtering approach failed

causing real time playback errors and glitching in the audio playback. This resulted in replacing it using the fft.js library which resulted in accurate frequency response and audio playback.

Limitations

The model is a first order approximation of the human ear, it is not a completely accurate anatomical model and cannot be treated as such. Additionally, there is no loading between stages and the transfer functions are multiplied which doesn't represent the actual anatomy and impedance change of the ear. Lastly, the OME scenario is not clinically calibrated and is not to be used as a diagnostic model.