Mini Project 2: Actuator Characterization

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1. Introduction

Haptic feedback in wearable devices enhances human-machine interaction by providing additional sensory cues beyond visual and auditory signals. Selecting appropriate actuators is a crucial step in good haptic device design. The following report assesses appropriateness of an E-12041808 voice coil actuator from Soberton Inc. by applying the Thiele/Smalls acoustic model. This report covers the experimental conditions used to obtain the corresponding T/S model, compares the model predicted results to the experimental results and discusses the expected behaviour of the actuator when used in a skin contact haptic feedback device.

2. Methods

2.1. Setup

A USB Haptic Actuator Board (HAB) was used to simultaneously apply voltage signals and record voltage and current signals for all experiments in this report. Five different experimental conditions were implemented for the characterization; *Calibration, Wide bandwidth, Narrow bandwidth, Added mass,* and *Light touch*. Setup differences across these conditions are shown in Table 1.

Condition	Frequency range	Load component	Added mass
Calibration	1-10k Hz	10Ω resistor	
Wide bw	1-10k Hz	Actuator	
Narrow bw	1-500 Hz		
Added mass	1-500 Hz		0.15g disc
Light touch	1-500 Hz		Index fingertip pad

Table 1: Setup differences across different experimental conditions. 0.15g disc was taped to the center of the top of the actuator. Index fingertip pad rested on the top of the actuator without tape.

For all five conditions the basic electrical setup on Figure 1 was used, where the load component corresponds to the different combinations from Table 1.

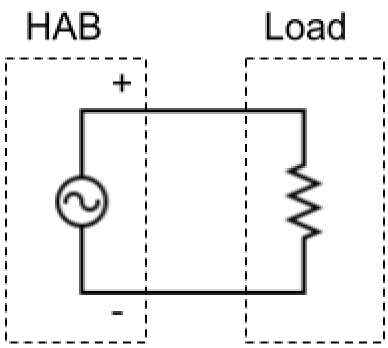

Figure 1: Basic electrical setup for all experimental conditions.

2.2. Procedure

Each of the experimental conditions in Table 1 was implemented in order to obtain all data for offline processing. The *Calibration* and *Wide bandwidth* condition results were processed before continuing with other conditions as a sanity check on device functionality and expected frequency of interest range. The following steps were performed for each of the conditions:

1. 60 second chirp signal generated in software with specified frequency range and 0.05 amplitude.
2. Implemented specific electrical and mechanical setup
3. Connected HAB to device running signal software via USB
4. Simultaneously played and recorded signals
5. Saved data for offline processing

2.3. Software

Audacity was used to generate, play, and record all signals in this report. A linear sinusoidal chirp signal with 0.05 amplitude was used for all experimental conditions. Data processing and plotting was done with Python and the following libraries/modules; numpy, scipy, matplotlib, sys, json, and os. All signals and scripts used in this report are linked in the appendix.

3. Results

Recorded .wav files were processed by converting data to voltage and current with a calibration factor from the

HAB data sheet. The data was then converted to the frequency domain with scipy.fft and plotted as impedance, following equation (1).

$$Z = \frac{V}{I} \quad (1)$$

Bode plots are shown for each of the experimental conditions in figures 2-6. Large spikes in impedance are observed at higher frequencies for the *Calibration* (Figure 2) and *Wide bandwidth* (Figure 3) conditions. Since these are only present at higher frequencies and are impulse-like they are likely noise or discontinuities from the electrical connections vibrating with the actuator and are ignored.

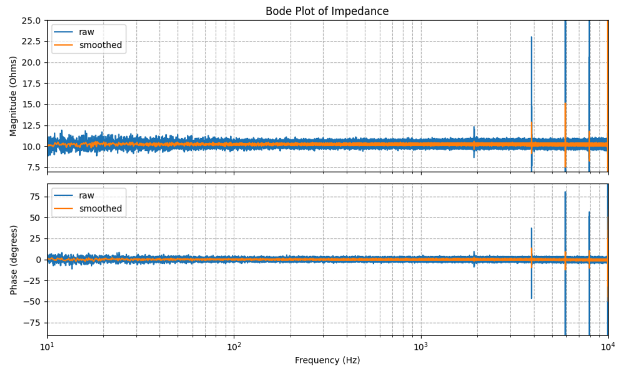

Figure 2: Impedance Bode plot of "*Calibration*" condition. Magnitude and phase match the expected 10Ω and 0° of the connected resistor.

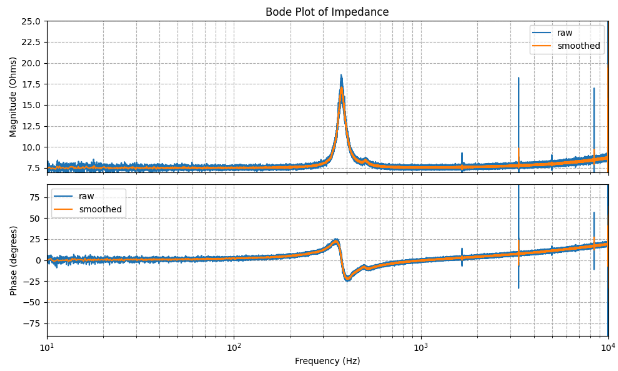

Figure 3: Impedance Bode plot of "*Wide bandwidth*" condition. The largest resonant frequency (between 300-500 Hz) matches the expected range of 1-500 Hz.

Additional observations of the wide bandwidth condition are that at high frequency (>5kHz) impedance begins to increase as the electrical inductiveness of the voice coil begins to affect impedance. At lower (1-2kHz) frequencies there is no significant increase in impedance, matching the expected results, supporting the decision to ignore the inductive effects during later modeling.

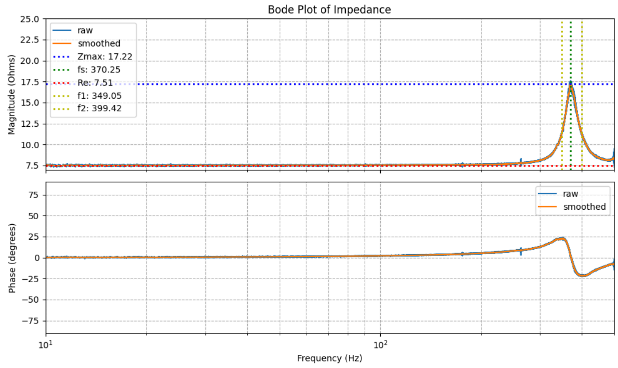

Figure 4: Impedance Bode plot of "*Narrow bandwidth*" condition. Free-air resonant frequency fs is 370.25 Hz for the smoothed signal.

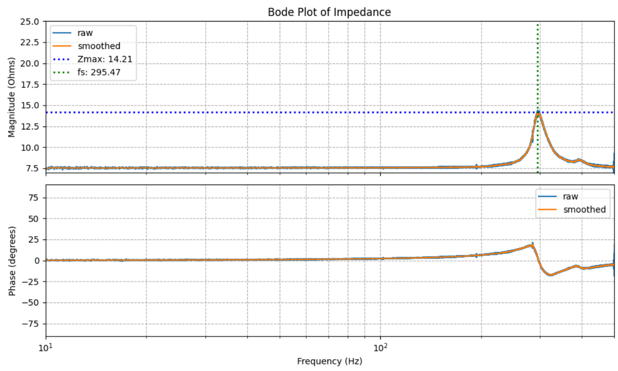

Figure 5: Impedance Bode plot of "*Added mass*" condition. Free-air resonant frequency fs is 295.47 Hz for the smoothed signal.

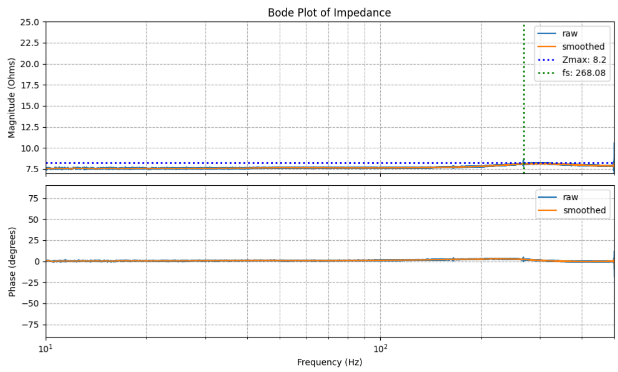

Figure 6: Impedance Bode plot of "*Light touch*" condition. Resonance amplitude Zmax is 8.2 Ω, significantly smaller than all other conditions. Free-air resonant frequency is 268.08 Hz.

4. Data Analysis

4.1. T/S Parameters

The results for the *Narrow bandwidth* and *Added mass* experimental conditions were used to extract the system parameters with the Thiele/Small (T/S) parameterization technique. Free Air Resonant Frequency (fs), Max Impedance (Zmax), Voice coil resistance (Re), and Resonant side frequencies (f1, f2) are plotted on the Narrow bandwidth plot (Figure 4) from where they were extracted. Quality factors Qms, Qes, and Qts were calculated with these values and equations 2-4.

$$Qms = \frac{fs}{(f2-f1)} * \sqrt{\frac{Zmax}{Re}} \quad (2)$$

$$Qes = Qms * (\frac{Zmax}{Re} - 1) \quad (3)$$

$$Qts = \frac{Qms*Qes}{Qms+Qes} \quad (4)$$

Mms, Cms, Rms, and BL parameters were calculated using equations 5-9 and the free-air resonant frequency from the Added mass condition results (fo = fs from Figure 5). Here the Δm is known as the 0.15g disc added mass to the system. Table 2 shows all parameters obtained for the characterization.

$$Mms = \frac{\Delta m}{\frac{fs}{fo}^2 - 1} \quad (5)$$

$$Cms = \frac{1}{(2*\pi*fs)^2*Mms} \quad (6)$$

$$Rms = \frac{2*\pi*fs*Mms}{Qms} \quad (7)$$

$$BL = \sqrt{(Zmax - Re) * Rms} \quad (8)$$

Parameter	Value
fs (Free Air Resonance)	370.25 Hz
Zmax (Max Impedance Magnitude at Resonance)	17.22 Ω
f1 (Resonance Side-band 1)	349.05 Hz
f2 (Resonance Side-band 2)	399.42 Hz
Qms (Mechanical Quality Factor)	16.85
Qes (Electrical Quality Factor)	21.77
Qts (Total Quality Factor)	9.50
Re (DC Coil resistance)	7.51 Ω
Mms (Equivalent moving mass)	$2.63*10^{-4}$ kg
Rms (Equivalent suspension damping)	$3.63*10^{-2}$ kg/s
Cms (Equivalent suspension compliance)	$7.02*10^{-4}$ m/N
BL (Force Factor)	0.59 Tm

Table 2: Experimental T/S parameters for E-12041808 voice coil actuator

4.2. Impedance Model

An equivalent electrical domain model is used to represent the full HAB + actuator system. Figure 7 shows the equivalent circuit used.

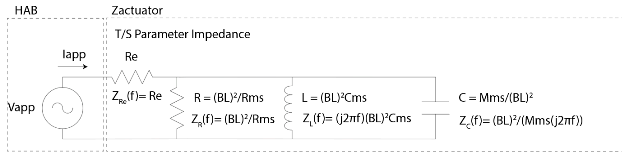

Figure 7: Equivalent electrical circuit used to model the HAB + actuator system.

The total modeled impedance is calculated with parallel and series circuit equations 9 and 10. Figure 8 shows the modeled impedance against the measured impedance from the *Narrow bandwidth* experimental condition.

$$Z_{parallel} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}} \quad (9)$$

$$Z_{series} = Z_1 + Z_2 \quad (10)$$

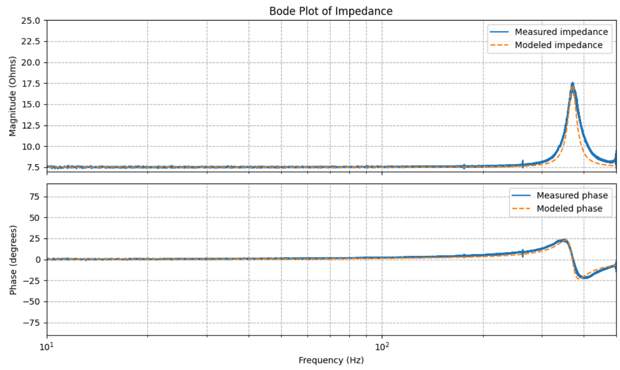

Figure 8: Modeled impedance from equivalent electrical model and T/S parameters against Measured impedance from "*Narrow bandwidth*" condition.

5. Discussion

This report presents the set of experiments conducted to characterise an actuator for use in a wearable device. The obtained Thiele/Small parameters produced an impedance model that acceptably matched real world measured impedance in the system (Figure 8). However, the model impedance at resonance differs from the measured impedance by having a narrower pulse width.

Several factors could account for this discrepancy. One possibility is a change in actuator stiffness between the Narrow bandwidth and Added mass conditions. Other potential sources of error include imprecise mass measurement in the Added mass condition or variations in external damping due to the actuator vibrating on the table. This last reason is a likely candidate as there was an audible difference in vibration of the device when the mass was added. Lowering the amplitude of the generated wave could reduce this vibration and improve the model performance, however it would require re-characterizing the actuator with updated conditions.

From the *Added mass* and *Light touch* experimental conditions, the resonant frequency and amplitude of the actuator are inversely affected by increased load mass. As actuators operate most efficiently near their resonant frequency and haptic perception is highly dependent on vibration frequency and intensity there are important implications to consider for use of the actuator in a haptic device. Attaching the device to different parts of the body would require re-characterization of the system to accurately produce the intended haptic sensation. Additionally a device that slightly shifts position such as a loose fitting wristband would require an adaptive control strategy, a much more complicated problem to implement than simply securing the device. These considerations highlight the importance of actuator characterization during haptic feedback device design.

References

[1] A. N. Thiele, "Loudspeakers in vented boxes: Part I," Journal of the Audio Engineering Society, May 1971.

[2] R. H. Small, "Vented box loudspeaker systems part I: Small-signal analysis," Journal of the Audio Engineering Society, June 1973.

[3] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, S. J. van der Walt, M. Brett, J. Wilson, K. J. Millman, N. Mayorov, A. R. J. Nelson, E. Jones, R. Kern, E. Larson, C. Carey, İ. Polat, Y. Feng, E. W. Moore, J. VanderPlas, D. Laxalde, J. Perktold, R. Cimrman, I. Henriksen, E. A. Quintero, C. R. Harris, A. M. Archibald, A. H. Ribeiro, F. Pedregosa, P. van Mulbregt, and SciPy 1.0 Contributors, "SciPy 1.0: Fundamental algorithms for scientific computing in Python," Nature Methods, vol. 17, no. 3, pp. 261–272, 2020, doi: 10.1038/s41592-019-0686-2.

[4] J. D. Hunter, "Matplotlib: A 2D graphics environment," Computing in Science & Engineering, vol. 9, no. 3, pp. 90–95, 2007.

Appendix

Github repo with collected data and "analysis.py" script used to produce all graphs in this report:
https://github.com/diegoasfmravpp/ECE598_MP2