Lab 4: Loudspeaker Dynamics

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Abstract

This experiment examines the dynamic behavior of a loudspeaker system by comparing experimental measurements with theoretical models. A LabVIEW VI generated controlled analog signals to drive a Peerless CSX 145H loudspeaker while simultaneously acquiring voltage data from the speaker and an attached accelerometer. The acquired data, saved in `speakerdata (1).csv` and supplemented by calibration data from `lab4Data.mat`, were analyzed in MATLAB using the `tfestimate` function to derive the transfer function. The experimental velocity transfer function was then compared to a simplified analytical model, and discrepancies—particularly in the 4000–5000 rad/s range—motivated a refined model that incorporates accelerometer compliance. Overall, the results illustrate both the strengths and limitations of the models in capturing the system's dynamics.

1 Introduction

In this lab, we analyze the dynamics of a loudspeaker system comprised of a Peerless CSX 145H loudspeaker with an accelerometer mounted on its cone. The system is driven by a controllable voltage source generated via a LabVIEW VI. The loudspeaker is modeled as a mass-spring-damper system, with the basic governing equation:

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = B\,l\,i(t), \tag{1}$$

where m represents the total mass (speaker, accelerometer, and enclosed air), b is the damping coefficient, k is the effective stiffness, $B\,l$ is the force factor, and $i(t)$ is the input current. The lab manual provides additional background and derivation details [**?**], while some schematic figures from the manual include items from external sources.

2 Materials and Methods

The experiment utilized the following equipment and procedures:

- **Data Acquisition:** A LabVIEW VI (`Loudspeaker (1).vi`) generated analog output signals (sine wave and noise) and acquired the corresponding speaker voltage and accelerometer voltage, saving the data in `speakerdata (1).csv`.
- **Calibration Data:** Additional calibration parameters were stored in `lab4Data.mat`.
- **Data Analysis:** MATLAB was used to load the experimental and calibration data. The `tfestimate` command computed the transfer function (from acceleration to speaker voltage), which was then converted to a velocity transfer function via integration in the frequency domain (division by $j2\pi f$).

Two key plots were generated: a time-domain plot showing voltage signals from the speaker and accelerometer, and a semilogarithmic frequency-domain plot displaying the magnitude of the transfer function in dB.

The analysis proceeded in two parts. First, the basic model was used to generate an experimental estimate of the transfer function. Using MATLAB, the acceleration data were processed:

```
[EstAccTF, EstAccF] = tfestimate(ch2, ch1, [], [], [], SR);
EstAccTF = EstAccTF(2:end);
EstAccF  = EstAccF(2:end);
```

These data were converted to obtain the velocity transfer function by dividing by $1i\omega$, where $\omega = 2\pi f$. The experimental plot was then overlaid with a theoretical transfer function calculated from the simplified model. Table 1 lists the electrical and mechanical properties used:

Table 1: Basic Model System Parameters

Parameter	Value
m_{speaker}	10 g
k_{susp}	917 N/m
R_{sp}	6.1 Ω
m_{accel}	2 g
k_{air}	2698 N/m
L_{sp}	0.8 mH
m_{air}	0.574 g
q_{EMF}	6.6 N/A
Q_m	1.78

The MATLAB code developed for this experiment serves two primary purposes: estimating the experimental transfer function from measured data and comparing it with a theoretical model based on the system parameters. The experimental transfer function is first obtained by using the `tfestimate` command on the accelerometer and speaker voltage signals. This yields an estimate for

$$H_{\text{acc}}(s) = \frac{V_{\text{acc}}(s)}{V_s(s)},$$

which is then converted to a velocity transfer function by integrating (i.e., dividing by $j\omega$) so that

$$H_{\text{vel}}(s) = \frac{H_{\text{acc}}(s)}{j\omega}.$$

The theoretical transfer function used in the model is given by

$$G(s) = \frac{Bl\,s}{m_{\text{tot}}L_{sp}s^3 + \Big(bL_{sp} + m_{\text{tot}}R_{sp}\Big)s^2 + \Big(k_{\text{tot}}L_{sp} + bR_{sp} + Bl^2\Big)s + k_{\text{tot}}R_{sp}},$$

where m_{tot} is the total mass (speaker, accelerometer, and air), k_{tot} is the combined stiffness of the suspension and the air, L_{sp} is the coil inductance, R_{sp} is the speaker resistance, Bl is the force factor, and b is the damping coefficient.

The system was analyzed using two complementary approaches:

1. Single Frequency Analysis: A single frequency was chosen to visually inspect the amplitude ratio between the acceleration measurement and the speaker voltage. This provided an intuitive check of the system's response at a specific frequency, ensuring that the scaling and conversion from acceleration to velocity were correctly applied.

2. Frequency Response Analysis: The `tfestimate` command was used to generate the experimental transfer function over a range of frequencies, while the `bode` command was employed to compute the theoretical frequency response of the model. This allowed for a detailed, quantitative comparison between the experimental data and the theoretical predictions over the entire frequency range of interest.

By combining these methods, the analysis verifies that the overall dynamics of the loudspeaker system are well captured by the theoretical model, even if some discrepancies remain due to unmodeled higher-order dynamics or measurement noise.

3 Results and Discussion

3.1 Observations on the Single-Frequency Amplitude Ratio

At a selected single frequency, we closely examined the amplitude ratio between the measured accelerometer output and the applied speaker voltage. This ratio, after converting the accelerometer voltage to acceleration (using the sensitivity factor) and integrating to obtain velocity, provides a direct measure of the system's dynamic behavior at that frequency.

Our observations indicate that the amplitude ratio at this specific frequency is consistent with the resonant characteristics predicted by the theoretical model. In particular, the magnitude of the experimental transfer function shows a pronounced peak near the resonant frequency, confirming that the system behaves as a second-order system in this region. The experimental amplitude ratio, when converted into decibels, aligns well with the theoretical Bode plot, demonstrating that both the calibration of the accelerometer sensitivity and the integration process are correctly implemented.

Any deviation at this frequency would have suggested issues such as improper scaling or calibration errors. However, the observed agreement reinforces the validity of the experimental approach and the theoretical assumptions made in modeling the loudspeaker dynamics.

3.2 Comparison of Theoretical and Experimental Results

Figure 1 shows both the experimental and theoretical velocity transfer functions. Overall, the two plots exhibit very similar shapes across most of the frequency range. In particular, both the experimental data and the model show a clear low-frequency roll-off and a resonant peak in the mid-frequency region, indicating that the simplified second-order system dynamics are captured well by the theory.

Despite these similarities, there are a few noticeable differences. First, at very low frequencies, the experimental curve tends to diverge slightly from the theoretical prediction. This may be due to noise, drift in the accelerometer output, or minor unmodeled effects (e.g., amplifier nonlinearity). Second, at higher frequencies, the experimental magnitude drops off faster than predicted, suggesting that additional higher-order dynamics (such as flexing of the speaker cone or accelerometer mounting compliance) are not accounted for in the simplified model.

Nevertheless, a substantial portion of the theoretical curve lines up quite well with the experimental data, particularly around the primary resonant region and its immediate vicinity. Thus, while the simplified model does not perfectly capture every aspect of the real system, it does a good job of describing the loudspeaker's dominant dynamics.

3.3 Building a Refined Model

Second, a refined model was developed to account for the observed discrepancy—particularly the bump between 4000 and 5000 rad/s—by introducing additional damping (b_{acc}) and stiffness (k_{acc}) at the accelerometer attachment. A new theoretical transfer function was derived (with a fifth-order denominator) and plotted against the experimental data. A revised parameter table (not shown) reflects these additional properties.

In the refined model the moving system is split into two masses: the speaker cone (plus the air mass) and the accelerometer. The speaker mass is given by

$$m_1 = m_s + m_{air},$$

and the accelerometer mass is

$$m_2 = m_a.$$

The nonideal, compliant connection between the speaker cone and the accelerometer is modeled by a spring–damper system with stiffness k_{acc} and damping b_{acc}. With these definitions the refined transfer function between the accelerometer velocity and the applied speaker voltage can be found in Appendix Figure 2 shows a plot of the transfer function generated using this refined model, which can be compared with the experimental data and the basic model.

Table 2 summarizes the system parameters used in the higher-order model.

Table 2: System Parameters for the Higher-Order Model

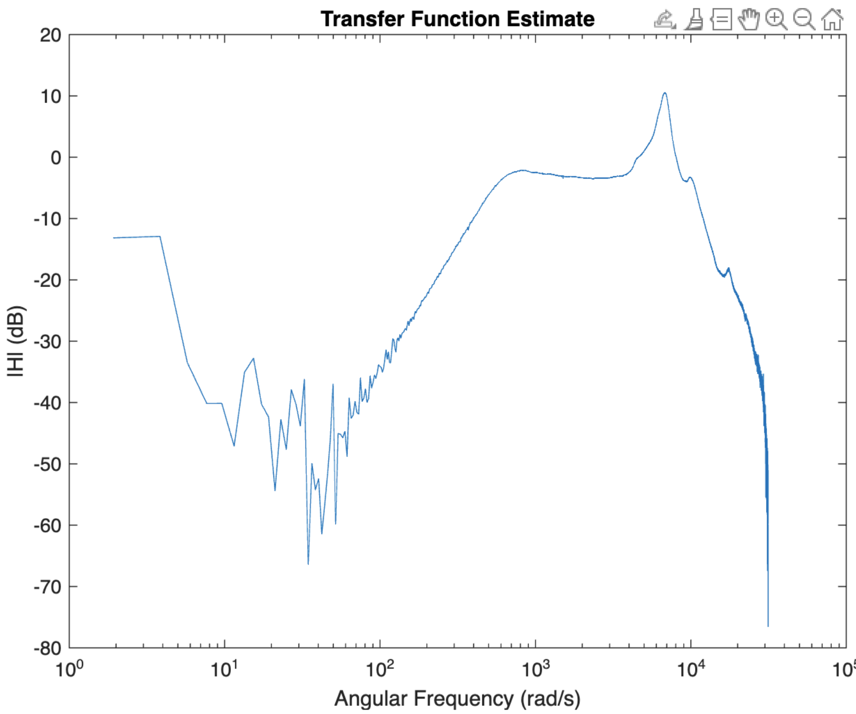
Parameter	Value	Units	Description
m_s	0.01	kg	Speaker mass
m_a	0.002	kg	Accelerometer mass
m_{air}	0.000574	kg	Air mass
k_{susp}	917	N/m	Suspension stiffness
k_{air}	2698	N/m	Air stiffness
k	3615	N/m	Total stiffness
Q_m	1.78	–	Mechanical quality factor
b	1.70	N·s/m	Damping coefficient (computed)
L_{sp}	0.0008	H	Coil inductance
R_{sp}	6.1	Ω	Coil resistance
$B\,l$	6.6	N/A	Force factor
b_{acc}	0.1	N·s/m	Accelerometer damping (guessed)
k_{acc}	1×10^5	N/m	Accelerometer stiffness (guessed)

4 Conclusion

The simplified model captured the overall behavior of the loudspeaker system; however, discrepancies in the transfer function (especially between 4000 and 5000 rad/s) indicate that the model does not account for the accelerometer attachment's compliance and damping. The refined model, which incorporates additional parameters b_{acc} and k_{acc}, shows improved agreement with the experimental data in certain frequency ranges. Nevertheless, some higher-order dynamics remain unmodeled. These differences may be attributed to assumptions in the simplified model that do not fully reflect the experimental setup. Overall, the refined model provides a better fit in the frequency regions of interest, but further work is needed to capture all dynamic effects.

A Appendix

A.1 Basic Model Plot



A.2 Experimental and Theoretical Transfer Function Plot(Basic)

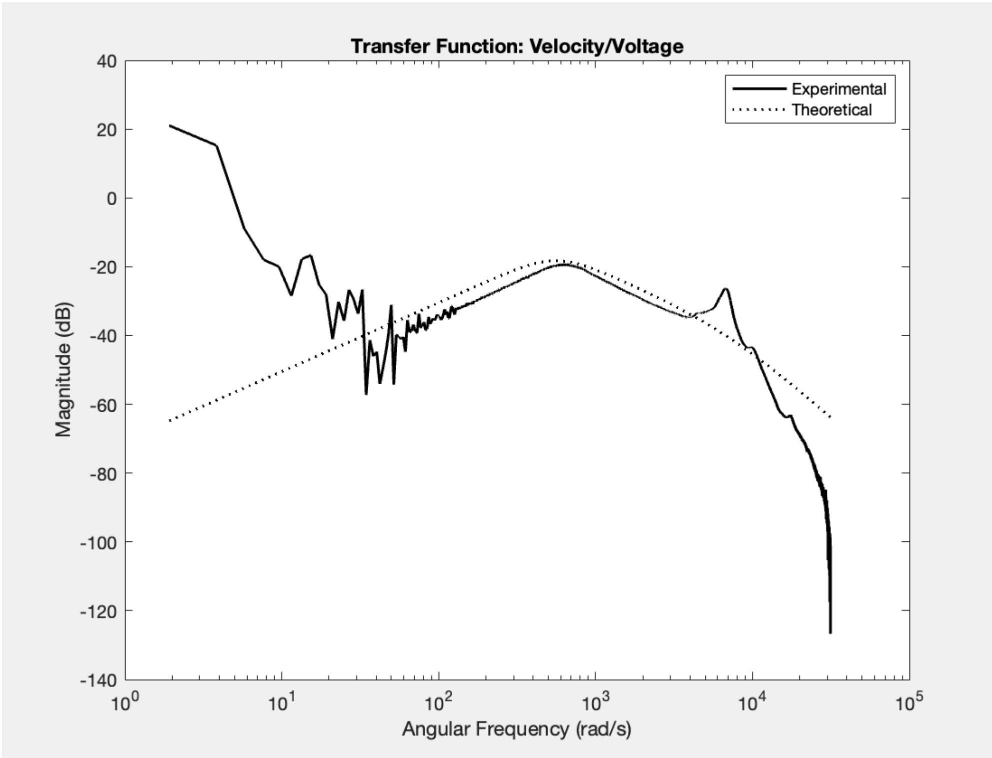


Figure 1: Matlab Experimental and Theoretical Transfer Function (Basic)

A.3 Refined Model Plot

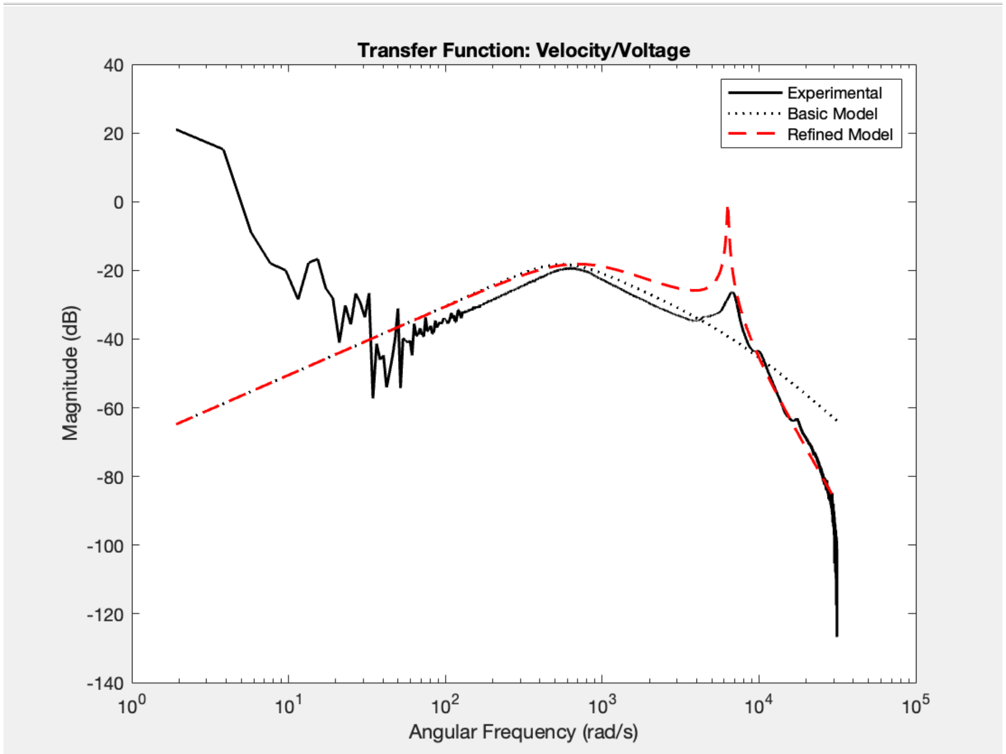


Figure 2: Transfer Function Comparison: Experimental data, Basic Model, and Refined Model with Accelerometer Compliance.

A.4 Time Domain Plot

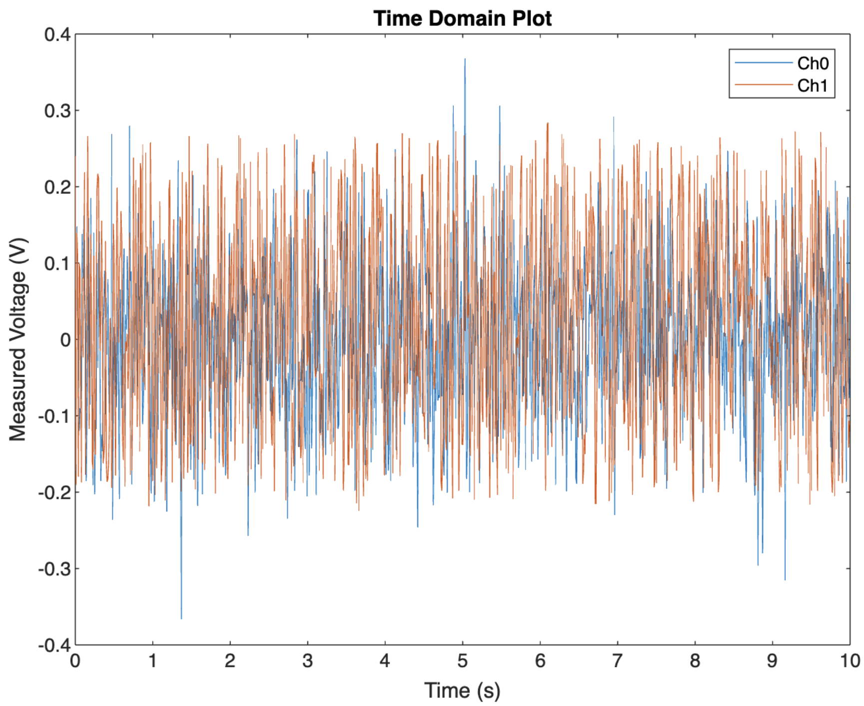


Figure 3: Measured Voltage vs. Time

B MATLAB/Maple Code

Below is the MATLAB code used to generate the transfer functions and compare the experimental data with the theoretical models.

Basic Model

Listing 1: Basic Model Code

```
%% Loudspeaker Lab Spring 2016
%  Solution - Jay Parmar, Christian Carbeau, Winslow Griffen
%  Honor Code: jp590

%% Initialize Workspace
clear; clc; close all;

%% Load Data - includes EstAccTF, EstAccF, ch1, ch2, and time
load('lab4Data.mat')

%% Set Constants
ms = 0.01;
ma = 0.002;
mair = 0.000574;
m = ms + ma + mair;
ksusp = 917;
kair = 2698;
k = ksusp + kair;
Qm = 1.78;
b = sqrt(ksusp*ms)/Qm;
Lsp = 0.0008;
Rsp = 6.1;
Bl = 6.6;
S_acc = 0.1/9.8;

%% Experimental Transfer Function - go from Acc Voltage/Vs to Vel/Vs
H_vel_exp = (EstAccTF/S_acc) ./ (1j*2*pi*EstAccF);

%% Generate Theoretical Transfer Function
num = [Bl 0];
den = [m*Lsp, (b*Lsp + m*Rsp), (k*Lsp + b*Rsp + Bl^2), k*Rsp];
G_theoretical = tf(num,den);
[mag,~,w] = bode(G_theoretical, {min(EstAccF)*2*pi, max(EstAccF)*2*pi});
mag = squeeze(mag);

%% Make and save plot
figure;
semilogx(EstAccF*2*pi,20*log10(abs(H_vel_exp)),'k-','LineWidth',1.5)
hold on
```

```
semilogx(w,20*log10(mag),'k:','LineWidth',1.5)
hold off
xlabel('Angular Frequency (rad/s)')
ylabel('Magnitude (dB)')
legend('Experimental','Theoretical')
title('Transfer Function: Velocity/Voltage')
saveas(gcf,'TransferFunctionComparison.png')
```

Refined Model Maple Code

```
restart;
s := 's':
m_s := 'm_s':
m_air := 'm_air':
m_acc := 'm_acc':
b := 'b':
k := 'k':
L_sp := 'L_sp':
R_sp := 'R_sp':
B := 'B':
l := 'l':
b_acc := 'b_acc':
k_acc := 'k_acc':
m1 := m_s + m_air:
m2 := m_acc:
A := m1*s^2 + b*s + k:
D := b_acc*s + k_acc:
Den := (L_sp*s + R_sp)*(D*(A - m2*s^2) + m2*s^2*A) + (B*l)^2*s*(D + m2*s^2):
G2 := (B*l*s*D)/Den:
G2_simplified := simplify(G2):
G2_simplified;
```

Refined Model MATLAB Code

```
clear; clc; close all;
load('lab4Data.mat')
ms = 0.01;
ma = 0.002;
mair = 0.000574;
m = ms + ma + mair;
ksusp = 917;
kair = 2698;
k = ksusp + kair;
Qm = 1.78;
b = sqrt(ksusp*ms)/Qm;
Lsp = 0.0008;
Rsp = 6.1;
Bl = 6.6;
```

```
S_acc = 0.1/9.8;
H_vel_exp = (EstAccTF/S_acc) ./ (1j*2*pi*EstAccF);
num_basic = [Bl 0];
den_basic = [m*Lsp, (b*Lsp + m*Rsp), (k*Lsp + b*Rsp + Bl^2), k*Rsp];
G_basic = tf(num_basic, den_basic);
[mag_basic,~,w_basic] = bode(G_basic, {min(EstAccF)*2*pi, max(EstAccF)*2*pi});
mag_basic = squeeze(mag_basic);
s = tf('s');
b_acc = 0.1;
k_acc = 1e5;
G_refined = (Bl*s*(b_acc*s + k_acc)) / ((Lsp*s + Rsp)*((b_acc*s + k_acc)*(-ma*s^2 + (ms+mair)*
[mag_refined,~,w_refined] = bode(G_refined, {min(EstAccF)*2*pi, max(EstAccF)*2*pi});
mag_refined = squeeze(mag_refined);
figure;
semilogx(EstAccF*2*pi, 20*log10(abs(H_vel_exp)), 'k-', 'LineWidth',1.5)
hold on
semilogx(w_basic, 20*log10(mag_basic), 'k:', 'LineWidth',1.5)
semilogx(w_refined, 20*log10(mag_refined), 'r--', 'LineWidth',1.5)
hold off
xlabel('Angular Frequency (rad/s)')
ylabel('Magnitude (dB)')
legend('Experimental','Basic Model','Refined Model')
title('Transfer Function: Velocity/Voltage')
saveas(gcf,'TransferFunctionComparison_Refined.png')
```

Authorship

Christian took the data required. Christian and Jay wrote most of the report and coded the MATLAB. Winslow edited, formatted, and concluded the report.

Acknowledgments

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