Lab 13

Loudspeakers

In this lab, you will bring together all of your experience with data-analysis techniques, Fourier spectral measurements, automated experiment-control and data-acquisition methods, and AC impedances to solve an interesting practical problem: design and build a crossover network to drive a loudspeaker.

13.1 Speaker Drivers

A loudspeaker is usually described as a multi-component system that includes an enclosure, two or more speaker drivers and an electrical crossover network. Have you ever wondered what physically differentiates a high-quality loudspeaker from a low-quality loudspeaker?

In the context of acoustics, a transducer is a device that converts mechanical (or acoustical) energy into an electrical current, whereas a generator does the opposite. In this context, a microphone is a transducer and a speaker driver is a generator. Both have physical responses that are time and frequency dependent. The time and frequency-response functions are related to one another via the Fourier transform. If the frequency-response function (FRF) were perfectly flat (i.e. frequency independent), then the output signal would always match the input signal – a very desirable outcome. Inevitably, however, real transducers and generators perform better at some frequencies than at others. A woofer driver, for example, is designed to respond strongly to low-frequency audio signals, but does not respond well to high-frequency signals. A tweeter, on the other hand, is designed to respond strongly to high-frequency audio signals, but not low-frequency signals.

The generic speaker driver in Fig. 13.2 is much like a damped driven mass-spring oscillator. The relatively solid “cone” is the moving mass. The “spider” and the “surround” are the springs, but also provide some damping. A small “voice-coil” electromagnet attached to the cone interacts with a stationary permanent magnet to produce a time-varying driving force. When an audio signal is applied to the voice coil, it excites a corresponding mechanical motion of the cone, which then generates pressure waves in the air outside the cone, which propagate...
outward as sound.

13.2 Loudspeakers

Ideally, we are looking for a flat FRF that leaves the input signal undistorted. It would be nice to have a single speaker driver that has a uniform FRF throughout the audio range (0 to 20 kHz). In practice real speaker drivers just aren't that good. A typical loudspeaker uses two or more drivers in parallel (see Fig. 13.3) with complimentary frequency response functions to cover different regions of the audio frequency range. Typical FRFs for woofer and tweeter speaker drivers are shown in Figs. 13.4 and 13.5. Observe that the woofer response in Fig. 13.4 is effectively that of a low-pass filter with a cutoff near 2 kHz, whereas the teeter response in Fig. 13.5 is effectively that of a high-pass filter with a cutoff near 1.5 kHz.

![Figure 13.3 A woofer (bottom) and tweeter (top) connected in parallel using a very basic crossover network.](image)

![Figure 13.4 Frequency response (Hz) of a woofer measured in our lab.](image)

![Figure 13.5 Frequency response (Hz) of a tweeter measured in our lab.](image)

The idea is to combine these two FRFs so that a wider range of frequencies can experience uniformly strong gain (see 13.6). As long as the individual ranges of the drivers have some overlap (to avoid frequency gaps), the entire audio range can be covered. Unfortunately, real drivers have mechanical and acoustical resonances that further complicate the gain curves. A more expensive driver will usually be flatter over a wider range. The FRFs of the various drivers also need to be balanced because we don't want the tweeter to have a much larger response at 10 kHz than the woofer has at 500 Hz.
13.3 Crossover Network: Concept

We want to selectively send to each driver only the frequencies in its designed range. This is accomplished with an electrical crossover network, which splits the input signal into several different outputs, each of which is filtered to match the right frequency range of a given driver. A crossover network can be as simple as the inline capacitor and inductor shown in Fig. 13.3.

To better appreciate the crossover network, consider the two circuits shown in Fig. 13.3, where we take (for simplicity sake) the impedance of each speaker to be purely resistive with values $R_W$ and $R_T$. The inductor inserted in the line to the woofer then creates an LR circuit. In lab 7 you studied the frequency response of a low-pass LR filter (see Fig. 13.7). The gain is given by

$$|G_W| = \left| \frac{R_W}{Z} \right| = \frac{R_W}{\sqrt{R_W^2 + (\omega L)^2}} = \frac{1}{\sqrt{1 + \omega^2 (L/R_W)^2}} \quad (13.1)$$

If you choose the cutoff wisely, this electrical circuit will pass only the low frequency range that matches the mechanical/acoustic response of the woofer so that the woofer never receives frequencies that it can't handle.

The capacitor inserted in the line to the tweeter creates an RC circuit. In lab 8, you studied the frequency response of a high-pass RC filter (see Fig. 13.8). The gain is given by

$$|G_T| = \left| \frac{R_T}{Z} \right| = \frac{R_T}{\sqrt{R_T^2 + (1/\omega C)^2}} = \frac{\omega R_T C}{\sqrt{1 + \omega^2 (R_T C)^2}} \quad (13.2)$$

Again, you can choose the cutoff frequency of this electrical circuit to pass only the high frequencies that match the mechanical/acoustic response of the tweeter. When the high and low frequency cutoffs of the two crossover channels are made equal (i.e. $L/R_W = R_T C$), the rules of parallel-circuit addition (see section 9.4) leads to an exactly flat gain curve, as seen in Fig. 13.9:

$$|G_{net}| = \sqrt{|G_W|^2 + |G_T|^2} = 1 \quad (13.3)$$
What could it hurt to just send the total input signal to both drivers, since they won’t respond well to frequencies outside their respective ranges anyway? There are at least two important reasons to use a crossover network. 1) In an frequency-overlap region, where two adjacent drivers both produce significant output, the two drivers become acoustically coupled via the pressure waves that they generate. In this way, one driver can modify (i.e. degrade) the FRF of another driver. 2) The waves produced by the two drivers can interfere to create strange spatial distributions in the sound intensity.

13.4 Crossover Network: Implementation

In this lab, you will build a simple first-order two-way (i.e. two driver) loudspeaker system with one woofer and one tweeter. After splitting the signal into two branches, you will want filter the woofer signal with a low-pass RL filter and the tweeter signal with a high-pass RC filter. By setting the cutoff frequencies of the two filters equal to one another, the the FRF of the overall loudspeaker system can be optimized to be as flat as possible. In Fig. 13.9, the separate responses of a low-pass RL filter and a high-pass RC filter have been tuned to a mutual cutoff frequency. More complicated filter circuits with sharper cutoffs (employed by most commercial loudspeakers) can reduce the amount woofer/tweeter overlap.

The enclosure is also an important component of the loudspeaker. It is typically designed to extend the low-frequency end of the response curve of the woofer. No woofer has a low-frequency response that stays flat all the way to zero frequency – they typically drop off somewhere between 100 and 200 Hz. The enclosure adds a mechanical potential-energy (i.e. analogous to a spring or a capacitance) to the system since the enclosed volume of air is compressed by a pressure wave. Combined with the mass of the driver cone, you get a mass-spring oscillator that can be tuned to resonate broadly just below the woofer’s low-frequency cutoff, effectively extending the low-frequency response of the system.

Take a moment to read the hyperphysics entry on crossover networks. This page is located at http://hyperphysics.phy-astr.gsu.edu/hbase/audio/cross.html. Notice that the electrical resistance of the driver itself can be considered to be a filter component. Ideally, one treats each driver in Fig. 13.3 as a simple electrical resistor (e.g. 8 Ω) in order to obtain the desired high- and low-pass filter FRFs. But in reality, the electrical, mechanical and acoustic dynamics of a speaker driver are coupled, resulting in an effective electrical impedance that acts like a more complicated LRC network. The network in Fig. 13.3 is common but very unsophisticated.

The above hyperphysics site also shows you how to use a parallel resistance to reduce the output from the tweeter. This "balance" resistor allows you to reduce the sound intensity of the tweeter to match that of the woofer. In this lab, we will compensate for any imbalance by simply moving the mic closer to one driver than the other. But at least you know how to apply a balance resistance if you need to.
13.5 Measuring the Frequency Response Function

There are several approaches to measuring the FRF of a loudspeaker. We will mention three here.

1) As in previous labs in which you measured the FRFs of electrical, mechanical and acoustical systems, you can manually sweep the frequency of a sinusoidal input signal over a wide range of frequencies to see the gain at a number of points along the way. This is called the continuous wave (CW) approach.

2) You can send in a very sharp input pulse, and measure the acoustic time response with a microphone, which can then be Fourier transformed to find the FRF of the driver. In lab 12, you found that a pulsed signal (e.g. a hand clap or a balloon popping) produces a very broad frequency spectrum (with synchronized phase). An infinitely-sharp pulse, if it can be produced, provides a perfectly flat input frequency spectrum.

3) You can send random noise (or static) into the loudspeaker (see Fig. 13.10). Such a signal is often called white noise because it contains a uniform mixture of frequencies with random phase, much like incoherent sunlight, which has a quasi-uniform (i.e. white) spectrum over the visible range. This is perhaps the easiest and most commonly used approach for testing acoustical equipment. You will use this approach to characterize your drivers. One simply sends an artificially-generated white-noise electrical signal into the driver, and measures the frequencies picked up by a microphone.

Figure 13.10 White noise.
One important caveat: we have ignored the fact that the other components in the experiment (the power amplifier, the microphone, the preamplifier, the output and input electronics, not to mention the echos in the room) also have their own FRFs. This situation is illustrated in Fig. 13.11, where the output of each component in the train becomes the input for the next component. The combined FRF is the multiplicative product of the individual FRFs of each of these components.

\[
\left( \frac{\text{output}}{\text{input}} \right)_{\text{train}} = \left( \frac{\text{output}}{\text{input}} \right)_{1} \left( \frac{\text{output}}{\text{input}} \right)_{2} \left( \frac{\text{output}}{\text{input}} \right)_{3} \ldots \left( \frac{\text{output}}{\text{input}} \right)_{n} \quad (13.4)
\]

Because any component with a flat response can be harmlessly ignored (multiplying by a constant doesn’t change the shape of the FRF), one might hope to assume that the auxiliary components all have flat frequency responses. But in reality, one needs to check auxiliary components very carefully to make sure that they don’t have severe frequency-response limitations. A multimeter, for example, loses sensitivity at frequencies above a few hundred Hz. A good oscilloscope, on the other hand, has a flat response from 0 to well beyond 2 MHz. Thus an oscilloscope can be used to directly determine the FRFs of the signal generator and amplifiers.

For simplicity, we will assume that all components except our speaker driver have flat responses that can be neglected. Our amplifier responses are flat enough to ignore. However, the responses of the microphone and the echos in the room are not. Thus, even your flattest FRF won’t look very ideal. A really expensive mic would help, as would doing the experiment in an anechoic chamber (i.e. no echo). Moving the mic very close to the drivers helps to minimize the echos from the room, though this trick is rather artificial.

### 13.6 Equipment

Computer and interface box, dynamic microphone, woofer and tweeter drivers, variable-volume loudspeaker enclosure, preamplifier, power amplifier, frequency-response VI, crossover network components.

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1 A *caveat* is fancy word commonly used in science that means a qualification or warning.
WARNING: *The speaker drivers are quite expensive and easily damaged.*

1) The diaphragms can be easily ripped or punctured. Touch them only lightly.
2) The speaker enclosure is heavy and should be lifted and moved with care. Do not drop it.
3) The quickest way to destroy your woofer driver is to change the enclosure volume without first breaking the seal on the adjustable back plate, thereby creating a large positive or negative pressure inside. First set the plate position with the plate laying face down, and then rotate it up to make and lock the seal.
4) The quickest way to destroy your tweeter driver is to feed it too strong a signal. A signal level that sounds great from the woofer will fry your tweeter. After changing the cables on any driver, always start at zero gain on the power amplifier and turn the gain up slowly until the sound level just begins to annoy your neighbors.
Quiz

Q13.1 The purpose of a two-way crossover network is to
(a) boost the low-frequency response of the woofer.
(b) enhance the high-frequency response of the tweeter.
(c) split the input spectrum into low and high frequency components for separate delivery to the woofer and tweeter.
(d) balance the overall volumes of woofer and tweeter.

Q13.2 In addition to the frequency responses of your speaker drivers, your measurements will inevitably detect the frequency responses of the other components in your signal train. Circle the two components with the largest non-uniform frequency responses.
(a) white noise source (analog output port).
(b) power amplifier.
(c) the room.
(d) microphone.
(e) signal preamplifier.
(f) analog input port.

Q13.3 Which of the following actions will NOT damage your loudspeaker drivers?
(a) Failing to turn the power-amp gain knob to zero before and/or after changing the wiring to a driver.
(b) Moving the back wall of the enclosure without first breaking the pressure seal.
(c) Sending too strong a signal to the tweeter.
(d) Jamming a pencil through the woofer cone.
(e) Playing great 80’s music in stereo.

Q13.4 If your 8-Ω woofer and tweeter both have cutoff frequencies near 1200 Hz, compute the optimal values of \( L \) and \( C \) needed for a first-order Butterworth filter.
Exercises

A. Isolate the acoustical frequency responses of a pair of speaker drivers.

Form teams of no more than three students per station.

L13.1 Equipment configuration: The computer sends a white-noise signal out to your blue power amplifier from analog output A of your interface box (ao0), and then on to your speaker driver. Your microphone picks up the signal and feeds it through your preamplifier and into analog input 2 (ai1) of the interface box, where it is Fourier transformed and the frequency response displayed. A third BNC cable tees off from output A and runs into input 1 (ai0) of the interface box as a reference signal. On the microphone preamplifier, set the coarse gain to 20 and the fine gain all the way up. On the power amplifier, use the line input and set the gain knob ALL THE WAY DOWN.

L13.2 Labview configuration: Copy FrequencyResponse.vi into your own workspace. Explore the front panel and block diagram of the VI. The Getting Started panel shows you how to hook up the external cables. The FRF panel shows the magnitude of the computed frequency response function (i.e. the Fourier transform). The DAQ settings tab should be preset with correct default values so that you don’t need to modify them (though you will need to change the input ports if ao0 or ao1 don’t work on your interface box). In the FRF settings tab, set the number of samples to 10,000 (i.e. 0.5 seconds) with a Hanning-type apodization window. Set the averaging controls to 30 measurements, RMS averaging, exponential weighing, and one-shot repetition. Try a few test measurements – start the VI and turn the power amplifier gain up slowly until the speaker volume just begins to annoy your neighbors.

L13.3 Isolate the acoustic frequency response of your woofer driver over the range from 0 to 10 kHz (loudspeaker enclosure should be completely open in back). Place the mic up close to the driver (2 or 3 inches). After having your TA check to make sure that your frequency response looks reasonable, plot it (cut and paste from VI front panel into MS Word) and describe it in your lab notebook. You can blink the room lights to signal others in the room that you are taking data.

L13.4 Carefully install and seal the back plate of your loudspeaker enclosure. Now repeat the FRF measurement and plot the new FRF. Describe how the enclosure modifies the low-frequency end of the FRF. Try several different positions of the back plate, and describe the effect of enclosure volume on the low-frequency end of the FRF.

L13.5 Measure the acoustic frequency response of your tweeter driver over the range from 0 to 10 kHz. Because the tweeter is self-enclosed, it
doesn't matter whether or not the large enclosure is sealed. Plot and describe the tweeter FRF. How does it differ from the woofer FRF?

B: Design and build a loudspeaker that includes your drivers, an enclosure, and a 2-way crossover network.

L13.6  Design a first-order two-way Butterworth crossover network that optimally combines your woofer and tweeter drivers to obtain the flattest possible frequency response function. The http://www.lalena.com/Audio/Calculator/XOver/ site may be helpful; but repeat the final calculations by hand in your lab notebook. Review your woofer and tweeter FRFs, and do your best to pick a crossover frequency near the middle of the region where their FRFs overlap. Then set the 3dB rollover points of the high and low-frequency channels of your crossover equal to the crossover frequency. You should consider which audio resistors, capacitors, and inductors are available in the lab as you develop your design. Use an RLC multimeter to measure the value of each component that you use, including the resistances of your 8-Ω drivers. The actual and printed values may differ.

L13.7  Build the crossover network that you designed (use a breadboard for any resistors or capacitors that you select). Use FrequencyResponse.vi to visually check the frequency-responses of the woofer and tweeter output channels to make sure that they work as expected (not for the notebook). Now drive both output channels simultaneously. Adjust the microphone position to balance the sound intensity from the two drivers. Try to obtain the flattest possible frequency response over the widest possible range. Use the optimal enclosure volume that you identified earlier. You may want to try a smaller capacitance if you get a lot of distortion in the frequency-overlap region. Plot your best FRF for your lab notebook. Consider the imperfections in your FRF between 10 Hz and 10 kHz, and describe further improvements (a better mic, a more sophisticated 3rd-order crossover network, an echo-free room, etc.) that would improve your FRF.

L13.8  The stereo-BNC adaptor cable will allow you to connect an ipod to the power-amplifier input. Have fun, but try to accommodate those who are still collecting data. Please do not put any music on the lab computers. If you find that your tweeter is a little too dominant (due to the fact that we didn't require you to properly balance your drivers), suppress the tweeter intensity by placing an appropriate resistor in parallel with the tweeter driver and modifying the associated capacitance accordingly. For fun, you might want to try sending stereo-right signal to one loudspeaker and the stereo-left signal to another team's loudspeaker.