3-Way Loudspeaker Design and Construction

Alex Kulyk

PHYS 406 5/10/12

I. Introduction

The objective of this project was to design and build a stereo pair of 3-way “hi-fi” speakers using off-the-shelf drivers and an original design for the speaker cabinets. A crossover network would also be designed and implemented to compliment the characteristics of the speakers. The primary purpose of this design exercise was the associated learning experience, and good audio fidelity of the final product was not of the utmost importance.

While the quality of the end result was not the most important factor, design decisions were based around constructing speakers that follow accepted design criteria for good performance. To this end, the goal was a flat frequency response in order to allow for acceptable listening for a wide variety of music.

II. Initial Design Considerations

From the begging of the project, the plan was to design a vented 3-way speaker with a relatively flat frequency response of the range of approximately 50 Hz- 20 kHz. For aesthetic reasons, it was decided that the speaker cabinet be a traditional rectangular prism shape with a relatively narrow width compared to most commercially available 3-way, floor standing speakers. Because of the width constraint, smaller bass drivers would have to be used. In order not to sacrifice low frequency output, two identical woofers would be used in each cabinet. The mid and high frequency bands would be handled by a single midrange driver and tweeter, respectively.

A vented design was chosen in order to compensate for the higher low-frequency roll-off of the smaller bass drivers. In order to vertically accommodate 4 drivers and a vent per cabinet, and considering the necessary volume, the speaker would also be relatively tall, which was also part of the aesthetic goal of the project. The two, smaller woofer arrangement was also chosen for personal preference, as the designer prefers a tight, fast bass response over the more powerful and extended, but slower response of larger woofers

The crossover would be designed specifically for the drivers chosen, rather than using an off-the-shelf, preassembled crossover, in order to allow for flexibility in component choice. From the outset, the crossover design process seemed daunting due to the inherent non-ideal behavior of passive electronic components in complex audio circuits, and also due to the designer’s inexperience with circuit design.

III. Driver Selection

As previously stated, each of the speaker cabinets required 2 woofers, 1 midrange and 1 tweeter. A per-driver budget was decided upon, and the following drivers were chosen:

a. Dayton Audio RS180S-8 7" Shielded Woofer

   The RS180S-8 was chosen for its combination of small size and low frequency extension. The external width of the speaker cabinets was set at roughly 8.5", and the RS180S-8 is one of the largest woofers available that would fit comfortably in that dimension. The cone is made of aluminum, resulting in a favorable stiffness to weight ratio, allowing for larger cone excursion before the onset of distortion without the sluggish sound of heavier paper cones, which is especially important in drivers of this size. It also allows the cone to reach higher frequencies before cone break-up occurs, which happens when the cone ceases to move as a piston. This higher break-up frequency allows for more flexibility when choosing crossover frequencies, as will be discussed latter.

b. SEAS Prestige MCA12RC-H1304 Midrange Driver

   This midrange driver was chosen for its exceptionally wide and flat frequency response. The midrange is one the most important range to produce accurately, as the fundamental frequencies and important harmonics of many instruments fall directly in this band. The midrange is also the band in which humans are most sensitive to distortion. The SEAS has an almost flat frequency response from approximately 200Hz up to its breakup around 10kHz, again giving good flexibility for choosing both crossover frequencies.

c. SEAS prestige 29TFF/W-H1318 Tweeter

   This tweeter was chosen for its flat frequency response and for the fact that it is one of the few tweeters in its price range that extends beyond 20 kHz. While most humans can't hear beyond 20 kHz, and many are limited to significantly lower frequencies, a higher tweeter breakup frequency generally corresponds to a flatter response in the audible range. This tweeter also makes use of a waveguide to cover the magnet mounting screws in order to reduce diffraction. Another important factor in its selection was its low free air resonance frequency, which allows for more flexibility in choosing the upper crossover frequency.

IV. Cabinet Design

The cabinet design was to be tailored to the characteristics of the chosen drivers. It was helpful to have the external aesthetic design requirements before attempting to fully design the speaker cabinets, as it limited the number of degrees of freedom in the design process.

With the width fixed, the depth was chosen so that the ratio of internal cabinet depth to internal cabinet width was approximately 1.618:1. This is the golden ratio, and has been shown to be beneficial in avoiding overlapping resonance frequencies resulting from standing waves forming between the parallel walls of the cabinet.

At this point, Bass Box Pro 6 loudspeaker enclosure design software was utilized to determine the internal volume of the cabinet that would optimize the performance of the woofers. The bass response of a driver is very much dependent on the type and size of enclosure it is mounted in. It was decided at this point that it would be necessary to separate the midrange driver from the woofer enclosure because the large pressure forces inside the cabinet caused by the long excursions of the woofer cones can negatively affect the performance of the midrange drivers. The tweeter was mounted within the same enclosure as the midrange because its performance is not significantly affected by the volume of the enclosure in which it is placed. With the width of the cabinet fixed and the height of the midrange enclosure determined by the mounting positions of the tweeter and midrange, the depth was determined in order to yield the optimum volume. From here, the overall height was determined by establishing the necessary internal volume for the woofers.

With the overall dimensions of the cabinet set, 3 shelf braces were added in order to increase the stiffness of the cabinet and prevent the long side panels from resonating excessively. Significant portions of the material in the braces were removed in order to make them effectively acoustically transparent, while enough remained to provide significant bracing effects.

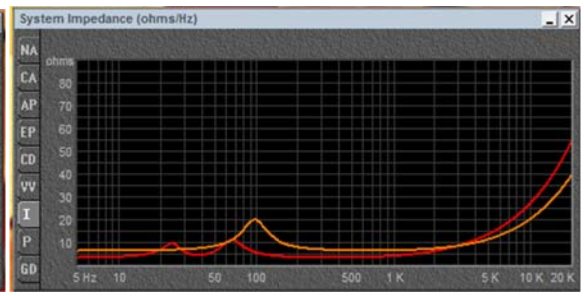
a. Port Considerations

In a vented cabinet design, a port of a specific length and diameter is constructed, leaving the inside of the cabinet open to the exterior. This port causes the cabinet to behave as a Helmholtz resonator. It resonates at a characteristic frequency, which is determined by the size of the cabinet and the acoustic mass of the air in the port, which, in turn, is determined by the dimensions of the port. The resonant frequency of the port is chosen so that the output of the port rises as the output of the woofers falls, thus extending the bass response further. At the port resonant frequency, all of the output is from the port. For this design, the port resonant frequency was approximately 40 Hz.

The length and diameter of the port are constrained by the necessary volume of air it encloses. It is important that the diameter of the port not be too small, as this not only results in an impractically large port length, but also results in a higher air velocity within the port. The movement of air can be audible at high speaker volumes due to the turbulence caused at the port ends, and is known onomatopoetically as “chuffing”. For this design, a diameter of 3” was sufficient, as flared port ends were also employed to further reduce the possibility of chuffing.

The physical placement of the port on the cabinet is generally not especially important, so long as it is not placed behind a driver, allowing the out of phase sound emitted from the back of the driver to escape the cabinet, distorting the sound heard at the listening position.

With all of the cabinet dimensions and variables determined, the cabinet was modeled in Pro/ENGINEER Wildfire 5.0. From this model, engineering drawings were produced that would be in valuable in the construction process. The cabinet was modeled acoustically in Bass Box Pro 6, which, although not especially sophisticated, was sufficient for the sake of this design. The BassBox simulations for the bass and midrange enclosures can be seen in the amplitude vs. frequency and impedance vs. frequency plots below.



V. Cabinet Construction

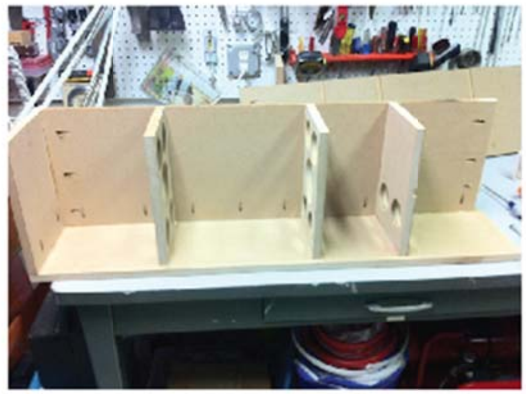
The cabinets were constructed of medium density fiberboard, more commonly known as MDF. MDF has desirable acoustic properties in that it has a completely uniform density throughout, unlike normal wood, and has a higher density than most other wood like materials. This has the benefit of mass damping, reducing the amplitude of the resonances of the panels themselves. The engineering drawings were used as references for all part dimensions.

The same lack of grain structure that gives MDF its superior acoustic properties makes it quite difficult when it comes to assembling the cabinets. Because of the way MDF is manufactured, mechanical fasteners do not hold well in it and can only be used to hold panels together while glue is drying. Due to the large size of the cabinets, pocket screws were used to hold the panels in place while the glue dried, and the pockets were subsequently filled with wood filler.

The cabinet was constructed so that the baffle would be removable to allow for easier installation of drivers and the crossover components and to allow for varying the amount of damping material within the cabinet to see its effects. This turned out to be a major challenge in construction, as threaded inserts had to be installed in order to accept the bolts that hold the baffle on. Most of the threaded inserts ultimately pulled out of the MDF, as the MDF could not support the repeated tightening and loosening involved replacing and removing the baffle.

All of the joints were sealed internally. Even with a vented cabinet design, small gaps in the cabinet can result in unwanted air noise cause by the large pressure differences between the inside on outside of the cabinet. Because the baffle was not yet permanently attached, gasketing tape was used on the edges where the baffle met the cabinet to provide an airtight seal.

The following series of photos shows the cabinet construction process.



VI. Crossover Design

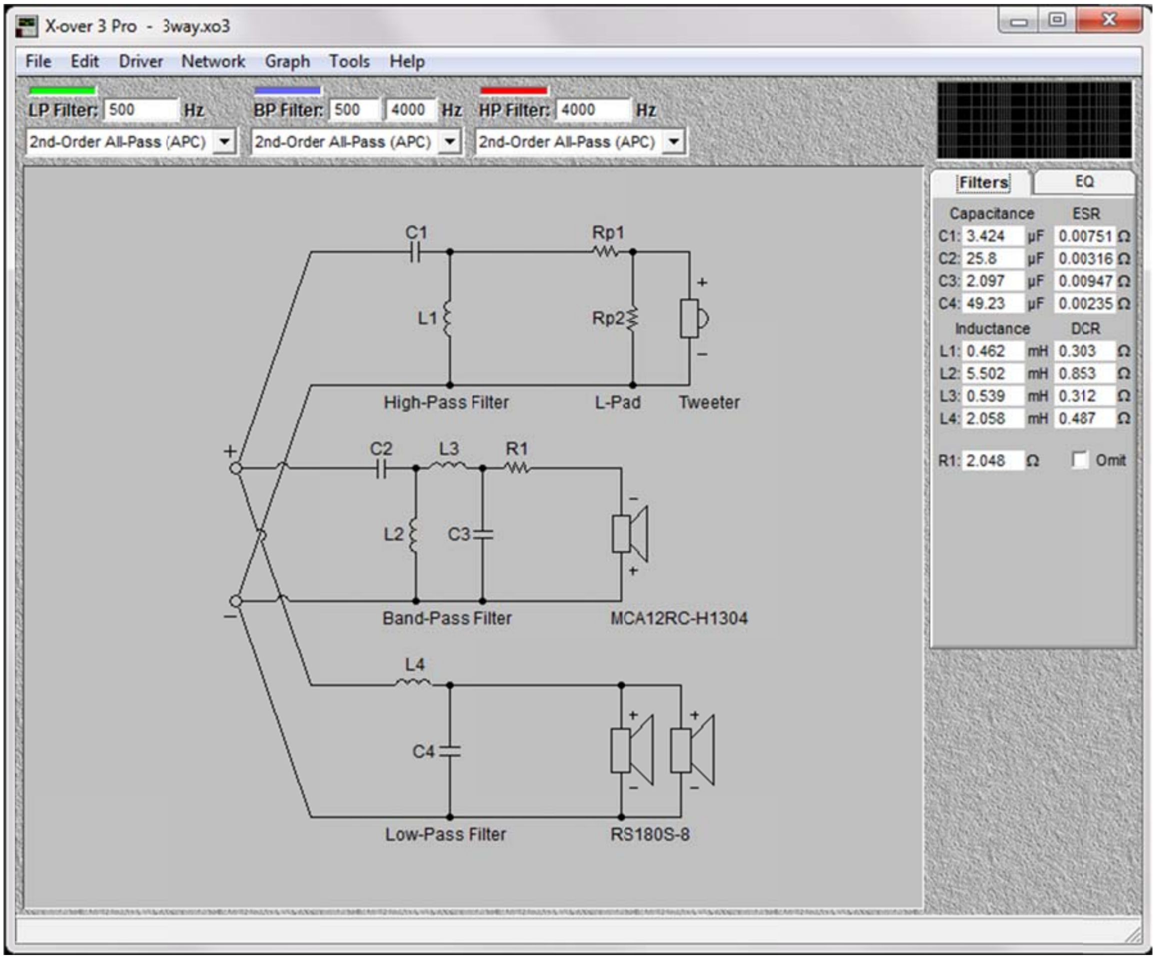
In a multi-driver loudspeaker, each driver is chosen because of its favorable operating characteristics over a specific frequency band. To ensure that the drivers are not subjected to signals outside of their specified frequency band, it is necessary to insert a set of filters, called a crossover, in the signal path. The function of the crossover is to distribute the desired frequencies to each driver, while also preventing unwanted frequencies from reaching the drivers. In a parallel, 3-way design such as this, it is necessary to employ 3 filters: a low pass filter for the woofers, a band pass filter for the midrange, and a high pass filter for the tweeter.

An ideal low pass filter allows all of the frequencies below a specified frequency to pass through unaffected, while blocking the frequencies above that. An ideal band pass filter allows all frequencies between two set frequencies to pass through the filter, while blocking all those outside the band. An ideal high pass filter blocks all frequencies below a certain frequency, and passes all those above that frequency through the filter.

Real world crossover implementations are far from ideal, especially in passive crossovers like the one used in this design. With passive components, it is impossible to achieve the infinite slope cutoff of the ideal filters described above. It is good practice to put 1-2 octaves between the crossover frequency and the closest driver resonance or break up frequency. First order crossover designs use the fewest number of components, thereby introducing the least amount of distortion to the signal, but only roll off at 6db/octave past the crossover frequencies. This is usually insufficient for 3-way designs, as each driver operates over a relatively narrow frequency band. For this project, a second order crossover network design was chosen because it requires fewer components than higher order networks, and has a sufficient 12dB/octave roll-off.

After installing the drivers in the assembled cabinets, the frequency response of each driver was measured in an attempt to locate crossover frequencies. The collected data showed no significant roll-off in any of the drivers within the measured bands, suggesting that the performance of the loudspeakers would not be affected significantly by the small variations in the choice of the crossover frequencies. From this information, the crossover frequencies were set at 600 Hz and 4,000 Hz.

Xover Pro 3 software was used to determine the circuit design and component values necessary for a second order network with the above mentioned crossover frequencies. The network is seen in the image below.

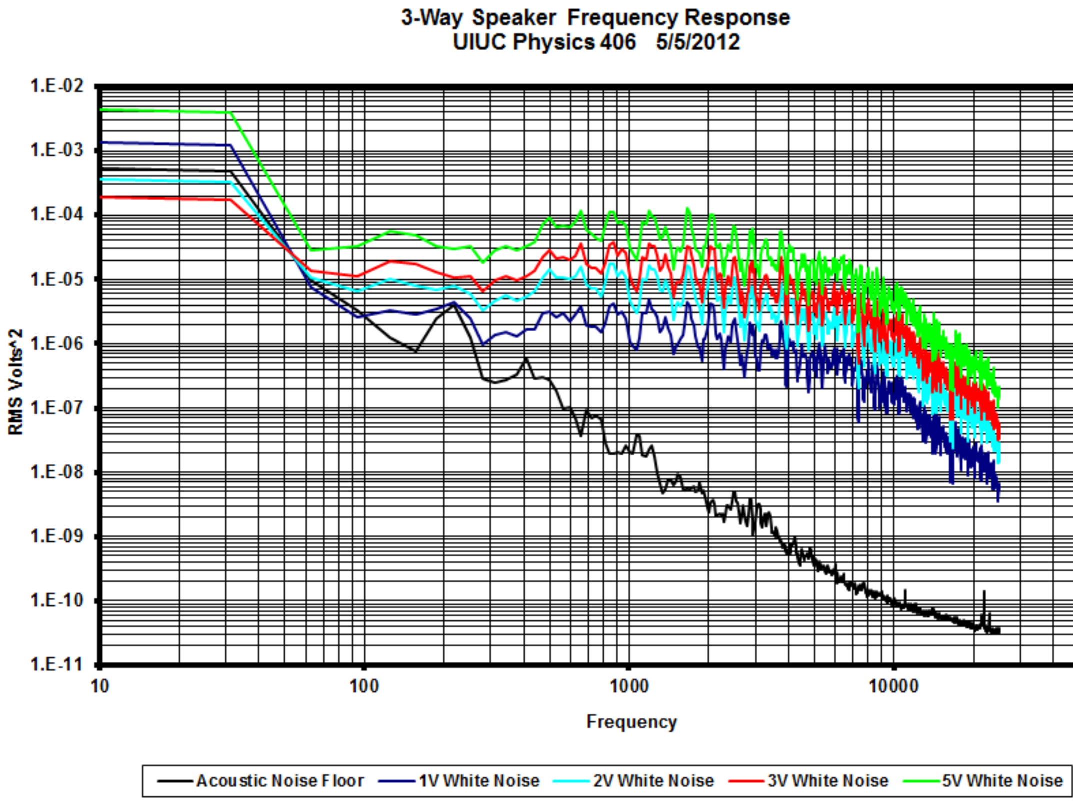


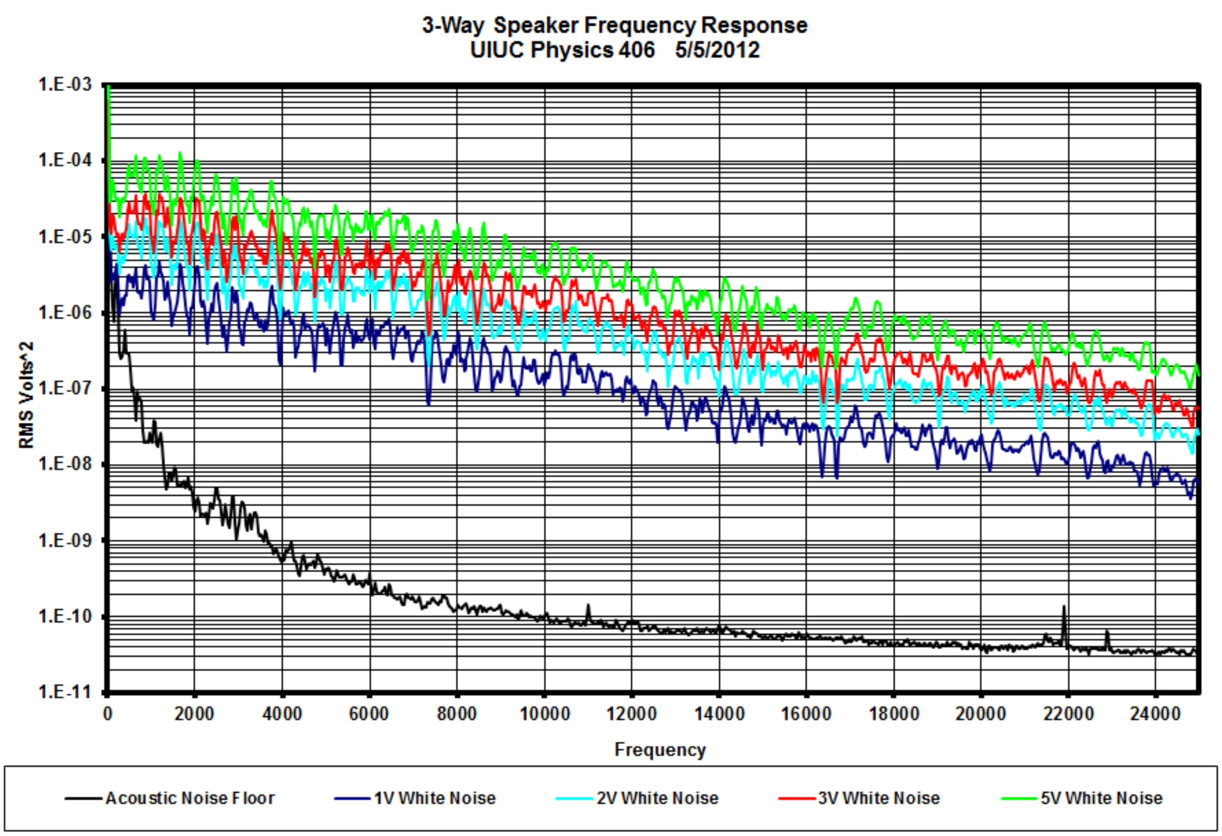
The tweeter high-pass filter contains a resistor network known as an L-pad, which reduces the output of the tweeter by approximately 4 dB. This is necessary because the tweeter is a significantly more efficient driver over the frequency band it is designed to operate in. Without this network, the tweeter would sound louder than the other drivers.

Crossover components were purchased on the basis of value-for-money. All capacitors have a 1% tolerance, so that the two loudspeakers sound sufficiently similar. The inductors are all 18-gauge air-core inductors to maintain a low DC resistance and avoid the distortion cause by iron-core inductors.

VII. Measurements and Analysis

One of the speakers was completed to the point that it was possible to take frequency response measurements. Measurements were taken using white noise ranging from 0 Hz-25 kHz. The microphone was placed at the midpoint between the center of the tweeter and the center of the bottom woofer, approximately 1m away from the speaker. Frequency response measurements of the amplifier used showed that it was very flat across the frequency range tested. The results of those measurements are shown below on the log V^2 vs. log f and log V^2 vs. f plots.


3-Way Speaker Frequency Response
UIUC Physics 406 5/5/2012
RMS Volts^2
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
10
100
1000
10000
100000
Frequency
Acoustic Noise Floor
1V White Noise
2V White Noise
3V White Noise
5V White Noise


3-Way Speaker Frequency Response
UIUC Physics 406 5/5/2012
RMS Volts^2
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
Frequency
Acoustic Noise Floor
1V White Noise
2V White Noise
3V White Noise
5V White Noise

The most noticeable characteristic of the plot is the consistent high frequency roll-off starting at about 1300 Hz, resulting in 20 kHz being approximately 6 dB down. This is likely due to the L-pad network implemented, suggesting that, because of the use of 2 woofers, the tweeter attenuation is unnecessary. Through the bass frequencies and over a good deal of the midrange, the response is acceptably flat, not varying by more than 3 dB in either direction. A small dip in the plot is visible at 4 kHz, the upper crossover frequency. This is characteristic of a second order filter network, and wiring the midrange out of phase with the tweeter and woofer, as it is in this design, minimizes the effect of that dip.

The fully assembled speaker was test with music played through a 50W/channel Rotel RA-1520 integrated amplifier. The frequency response plot is indicative of the sonic results. There is a pronounced recess to the high frequencies. The most troubling result, however, was a very “boxy” sound in the midrange. It is believed that this could be improved by reducing the amount of damping material in the midrange enclosure. It is also likely that the sonic character would be significantly improved if the baffle were rigidly attached to the cabinet with glue, rather than being bolted on, as in the current configuration, the braces do not eliminate any of the resonances in the baffle. Below is a picture of the speakers at their present state of completion.

VIII. Future Plans for this Project

In the next few weeks, both speakers will be completely assembled, with the baffles rigidly attached. I would like to take more comprehensive frequency, impedance and phase response measurements. From these plots, I could evaluate the validity of the simulations I produced in BassBox and Xover Pro. I would also like to compare any noted resonance peaks to calculated resonances.

It would also be interesting to characterize the frequency and phase response of the crossover network, and to see its effect on the speaker output.

After I finish construction, if the audio quality is good enough to merit it, I will veneer the cabinets so they are more aesthetically pleasing.