12/12/2008

Project 1

Design & Construction of 3-way Loudspeakers

Project by: Marc Daigneault

Project 1:
Design & Construction of 3-way Loudspeakers

Presented to: Dorian Braun

244-586-AB Project I

Department of Engineering Technologies

John Abbott College

Marc Daigneault
Student ID: 0686391

December 2008

Executive Summary

For the past 15 weeks, I have successfully designed and constructed a pair of 3-way loudspeakers in a custom MDF enclosure as my personal project for the Project 1 course. To ensure completion of the project in the 15 week time frame, I have split the task at hand into three separate categories: Driver selection, which deals with the selection of drivers that meet the demands of the project, Electronics, which deals with the design & assembly of the audio crossover, and Enclosure, which deals with the design & assembly of the speaker cabinet. This report contains the theoretical and practical work put into the project, as well as the final analysis of the loudspeakers performance, which was judged to be remarkable.

Introduction

For the Project 1 course, each student has the mandate to utilize the knowledge gained from the first 4 semesters in selecting, developing and implementing a project related to the applied physics component. At the end of the course, the student should have achieved the capacity to develop and implement a project, demonstrate project management and time management skills, and be able to demonstrate the results to the department in the form of both oral and writing presentations.

Therefore, to meet all the requirements and objectives of the Project 1 course, I have decided to research, design and constructed a pair of 3-way loudspeakers in a custom MDF enclosure.

This project involves many aspects that relate to the fields of electronics and audio, allowing me to apply the knowledge that I've acquired during my three years in the Engineering Technologies program, as well as profound my knowledge of audio systems and the complex theory behind them.

Proper preparation in the form of time management and project management will be performed, using methods such as planning, prioritizing, setting goals, being efficient and being proactive.

By selecting a project that balances being challenging and rewarding, and by using proper time and project management skills, I will have successfully completed this project in the 15 week time period, all while keeping control during the whole progress of the project.

Objective

My objective for Project 1 is to research, design and construct a pair of 3-way loudspeakers in a custom enclosure. I personally find this project to be challenging and of a fair level of difficulty, as it touches many fields related to the engineering technologies program, such as:

- Design, assembly and testing of electronic circuits
- Selecting, forming and finishing of the involved materials
- Computing, analyzing and fine-tuning the audio aspects of the project.

As well, I will design the system in such a way that it shall have a flat frequency response, within reasonable limits, which ultimately defines the performance of any loudspeaker system, as a system with a flat frequency response implies a realistic & accurate reproduction of sound. Once the construction of the loudspeakers is complete, I will be able, with the use of computer equipment, to verify the frequency response of the system and see if it corresponds with my objective of obtaining a flat frequency response.

Methodology

To ensure that I would reach my goal within the 15 week timeframe, I took a structured approach to the project to ensure that every step would be completed in a timely matter, keeping a log of time spent on the project and of every task completed.

As well, for proper project management, I delegated all the work that needed to be done into 3 distinct categories, which would allow me to prioritize task, as well as be more efficient with my time. These three categories are:

- Driver Selection
- Enclosure
- Electronics

As well as delegating each task, I created a timeline during the first week that contained the approximated time to be spent on each task, which guided me during the following weeks as to what needed to be done, as well as how much time I had planned to spend on each task. This ultimately allowed me to see my progress as the weeks went on, and gave me idea of where I was compared to where I should be.

Theory & Work

As described in the previous sections, I have split the task to be completed into three separate categories: Driver Selection, Electronics & Enclosure. I will address the theory and work put into each of these three categories respectively.

I. Driver Selection

The selection of the drivers is one of the most crucial parts of the project, as the characteristic of the drivers determine the properties of the enclosure and the electronics. When selecting which drivers to use, it’s important to consider many factors, such as:

- Number of speakers per enclosure
- Bandwidth of each driver
- Efficiency of each driver
- Thiele-Small parameters

The number of speakers per enclosure plays a crucial role, as each driver must be chosen to cover a portion of the entire bandwidth. This as well lowers the stress on each individual driver, and breaks up the whole bandwidth into 3 parts, one for each driver.

Since every speaker will only be covering a portion of the full bandwidth, it’s important that they be carefully selected to work in their designed range and that their efficiencies are matched (or attenuated in case they are different) so that the final output of the enclosure sounds as one whole speaker, and not as 3 independent ones.

Joining these properties with the Thiele-Small parameters, a collection of electromechanical properties of the drivers, I have made a selection of 3 drivers based on these properties, and have selected drivers that will work together nicely and that will help me reach my goal of obtaining a flat frequency response.

The drivers that I have selected are shown below, as well as the key parameters which lead me to choosing theses drivers over others.

a. Woofer: Dayton DC300-8 12" Classic Woofer

i. Frequency response: 28-2,500 Hz
ii. SPL: 92 dB 1W/1m

b. Mid-Range: Selenium 6W4P 6" Woofer

i. Frequency response: 80-9,000 Hz
ii. SPL: 91 dB 1W/1m

c. Tweeter : Goldwood GT-510 1" Soft Dome Tweeter

i. Frequency response: 3,000 - 20,000 Hz
ii. SPL: 90 dB 1W/1m

These drivers all have similar efficiencies, so no attenuation will be needed, which will simplify the construction of the electronics later. As well, each driver's bandwidth overlaps the other, which will mean that the combination of these three drivers will allow me to cover the whole audio bandwidth range, and allow for proper sound reproduction. As well, on a side note, each of the driver's impedance is matched (8 ohms), which will eliminate the need for Zobel impedance matching, thus again simplifying the electronics circuit. For more information, each manufacturer specification sheet for the respective drivers can be found in ***Annex 1***.

Now that the drivers have been selected, I can move onto the next portion of the project, which is designing the electronics for the 3-way crossover.

II. Electronics

The electronics portion of this project involved researching, designing and assembling the components for the 3-way crossover network. The crossover is an essential part of the system, as it splits the audio signal into separate frequency bands which can be handled by the 3 individual drivers. So by carefully designing the crossovers, I can obtain a full bandwidth reproduction from all three speakers working together.

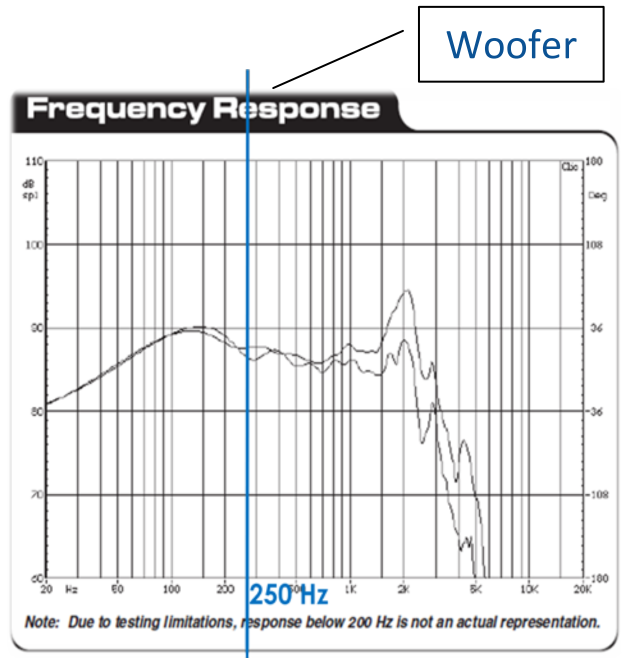
An important part of the crossover is ensuring that there is a smooth transition from one speaker to another, without dropping out too quickly form one speaker or jumping in to steeply on another. There are many different types of crossovers, all with specific advantages/disadvantages.

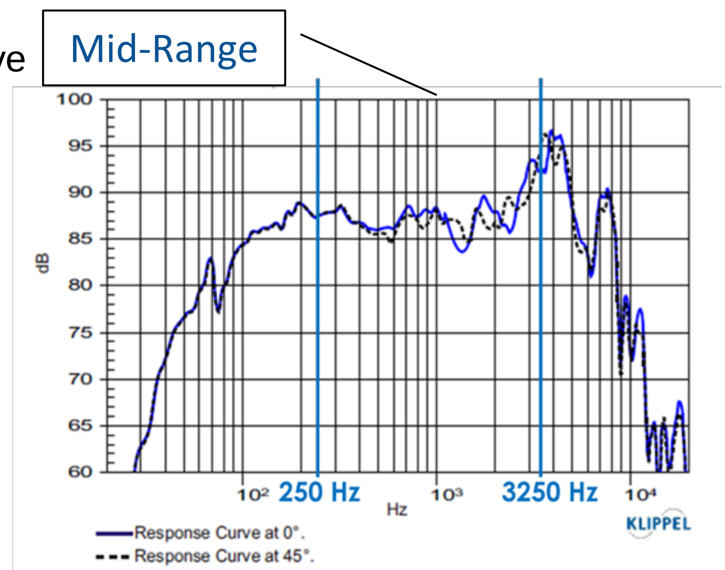
For this project, I chose to design a 2nd order Bessel type passive crossover. The 2nd order means that it's a 12dB/octave slope, an industry standard, which is a good amount of attenuation, and should allow for a proper transition from one speaker to another and allow the speakers to reproduce frequencies that are well within their designed capacities. The Bessel type is chosen because it offers a linear phase response, which is one of the highest priorities in speaker design.

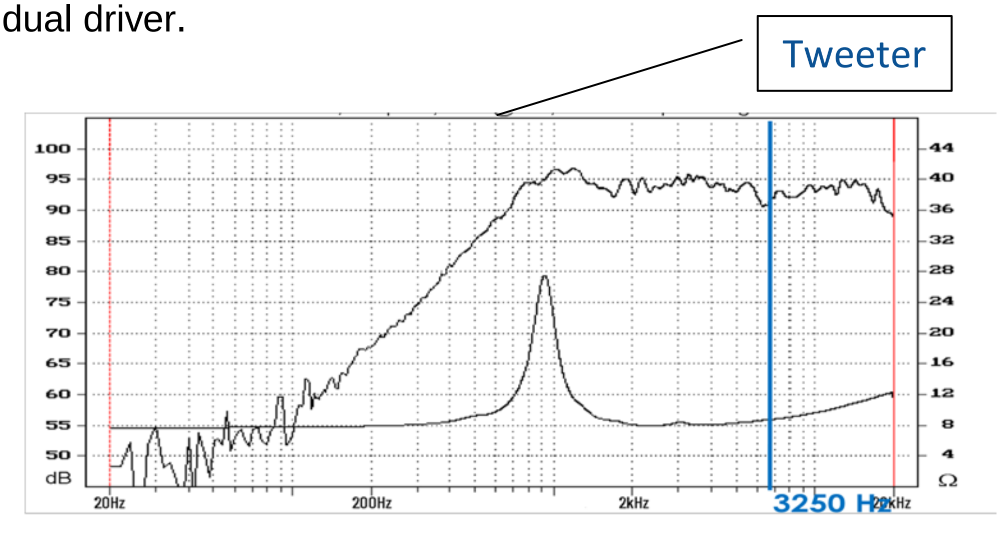
For the design of my crossover, I used computer simulation to determine the values of the components needed, which greatly simplifies the task of calculating the components of the RLC filter.

i. Picking the crossover points

The first task was picking appropriate crossover points. The crossover point determines which frequency will be used to split the audio frequency from one driver to another. The selection of the crossover point depends on the natural frequency response of each individual driver, as we want to start "crossing out" before getting out of the optimal performance range, and we don't want to "cross into" the next driver before it is in its optimal range as well. This is why it's crucial to have selected speakers that will work well together, and select crossover points that will allow a smooth transition from one driver to another. The full frequency response graphs for each driver can be found in ***Annex 1***; to the right I have included a quick glimpse at the selected crossover points on the frequency response graph of each individual driver.



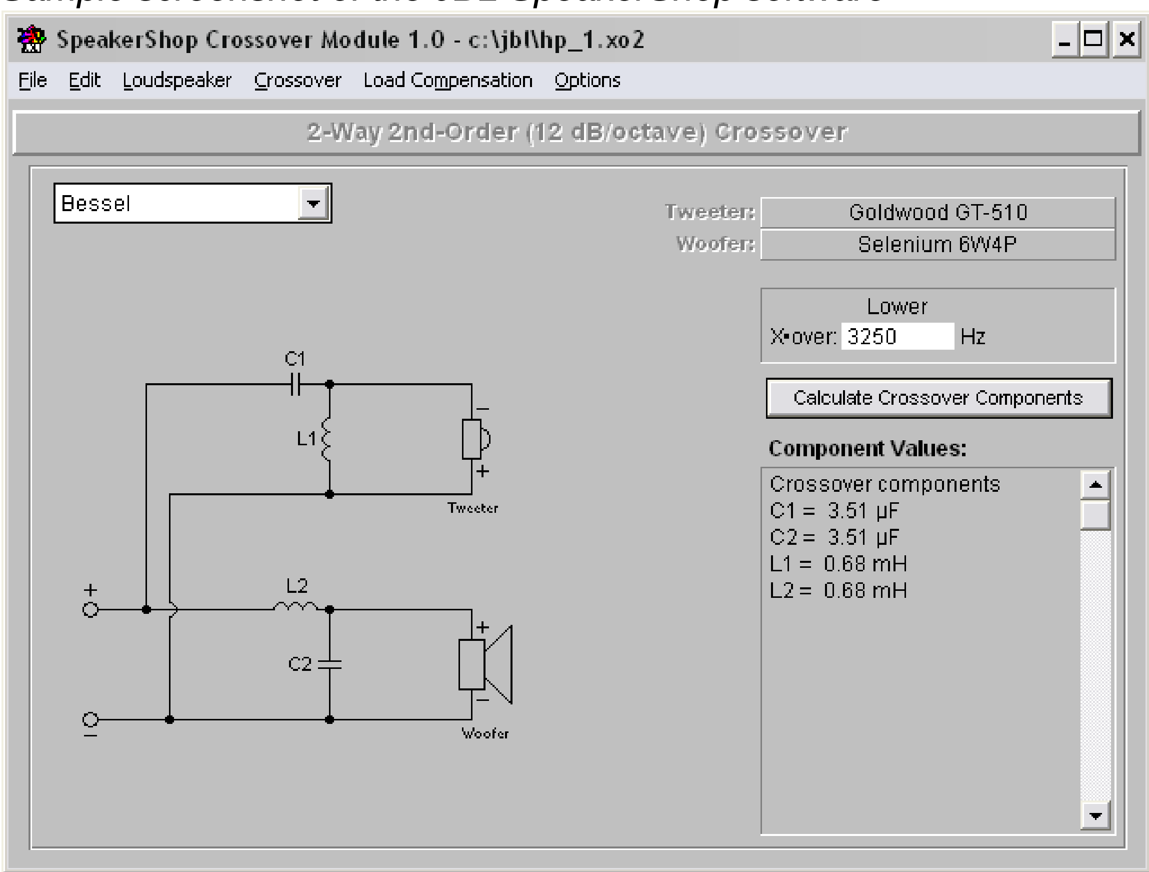




ii. Computer simulation in *JBL SpeakerShop Crossover Module*

Now that I have picked the crossover points, I can use software simulation to determine the component values for the RLC filter, with the use of the *JBL SpeakerShop Crossover Module*. By supplying the software with the Thiele-Small parameters for each driver, as well as the crossover points I have determined and the type of filter used (Bessel in my case), the software computes the results and give me the exact schematic and component values. In my case, this had to be done twice; once for the Woofer to Mid-Range crossover, and again for the Mid-Range to Tweeter crossover. Both screen captures can be found in ***Annex 2***.

Sample screenshot of the JBL SpeakerShop software



Once the component values were determined, I could now simulate the performance of the filter using *Electronic Workbench (EWB 6).*

Computer simulation in *Electronic Workbench 6 (EWB 6)*

Now that I have determined the component values needed for the crossover, as well as the schematic of the crossover, I can simulate the operation of the circuit in *EWB 6* and examine the output of the transfer function using a bode plotter. The bode plotter gives the output magnitude over the frequency range, and will allow me to see if there is any gain over the whole range of frequencies, which technically should have a constant, flat gain.

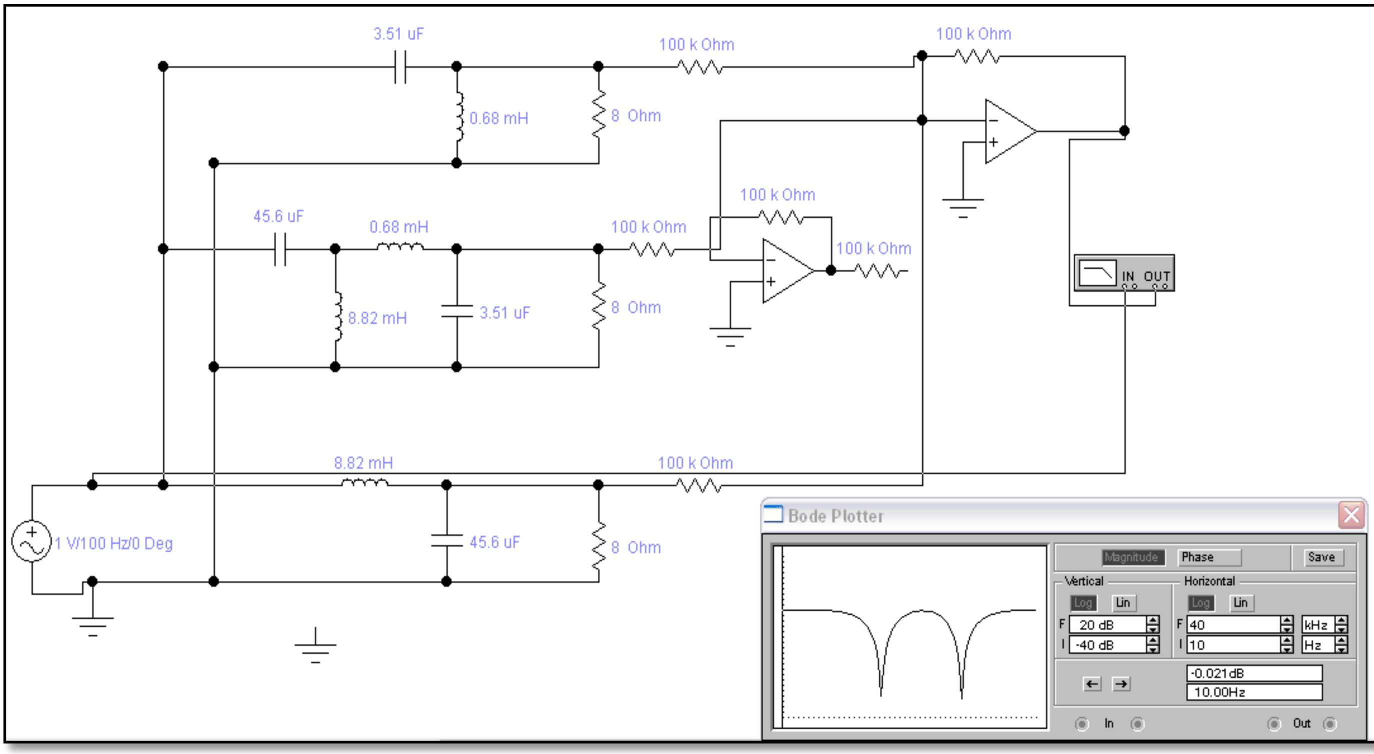
For the first simulation, I assembled the circuit as shown on the following page, and observed the output on the bode plotter, which perceptibly gave an unusual output: there were two negative peaks at the mid-range crossover points, which could only be explained by one thing: phase shift.

Due to the nature of the components of a passive filter, there are certain delays that are created in the circuit. As we can see, in the mid-range filter, there are essentially two sets of filters: a low pass and a high pass filter. The addition of these two filters adds a delay that isn't present on the woofer and tweeter portion, which essentially is delaying the mid-range by exactly 180°.

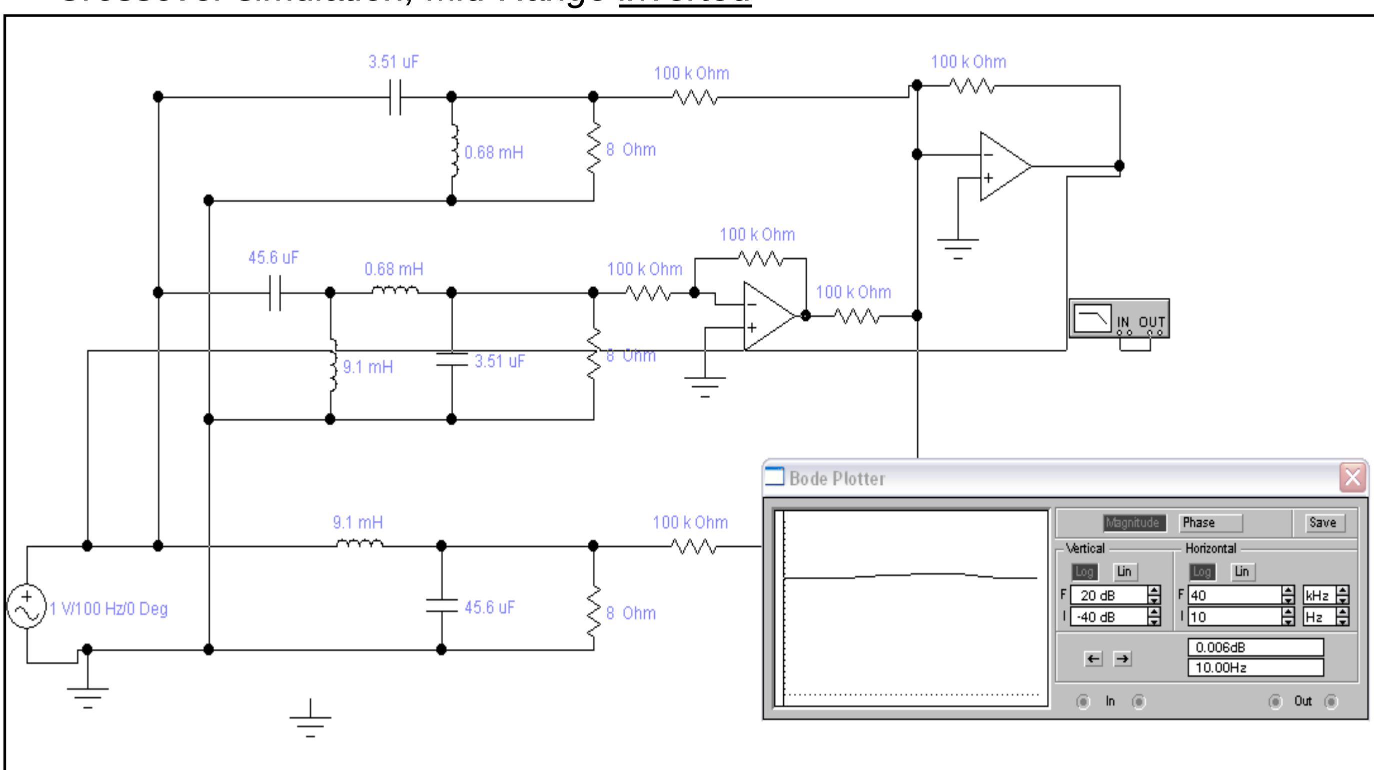
The easy solution for this problem is to inverse the connection to the mid-range driver, connecting the positive output of the filter with the negative input of the driver, and vice-versa. After having simulated this inversion in *EWB*, we can clearly see that the transfer function has a constant gain, which translates to a linear phase response and indicates that the crossover is properly designed to ensure that there are unwanted gains or losses from the electronics portion of this project.

The following page contains both EWB 6 simulations. The full page simulation can be found in ***<u>Annex 2</u>***.

Crossover simulation, Mid-Range not inverted



Crossover simulation, Mid-Range inverted



iii. Assembly of Crossover circuit

With the design of the crossover complete, the next step involved assembly of the crossover circuit. Two identical circuits were needed, one for each loudspeaker.

Although I had a schematic and the computed capacitor & inductor values, I was limited to whatever values of components are widely available on the market. Many of the computed components had very specific values, with most going into the 2 decimal places, so finding values that were suitable wasn't the easiest task. However, once all the parts collected, the computed values were spot on for some components, with others off by a decimal place or two.

Nonetheless, this modification to the parts had little to no difference in the transfer function of the crossover, as seen on the corrected *EWB 6* schematic screen capture in ***Annex 2***.

Now that the crossovers are assembled and ready to be put to use, I can move on to the next task of the project, which is assembling the MDF enclosure.

III. Enclosure

The third and final task of the project was to construct a pair of the custom MDF enclosures that would each house 3 drivers. The main goal of the enclosure is to reduce the transmission of vibrations from the drivers to the surroundings, and ensure that most of the power into the loudspeakers leaves as sound, and not lost in the mechanics of the enclosure.

To ensure limited loss via vibrations, the whole structure was constructed of 1” MDF; a solid, heavy enclosure that will surely limit the transmission of vibrations within the enclosure. For even more firmness, the internal structure was braced with strips of MDF, and sealed together with construction glue and 2” screws.

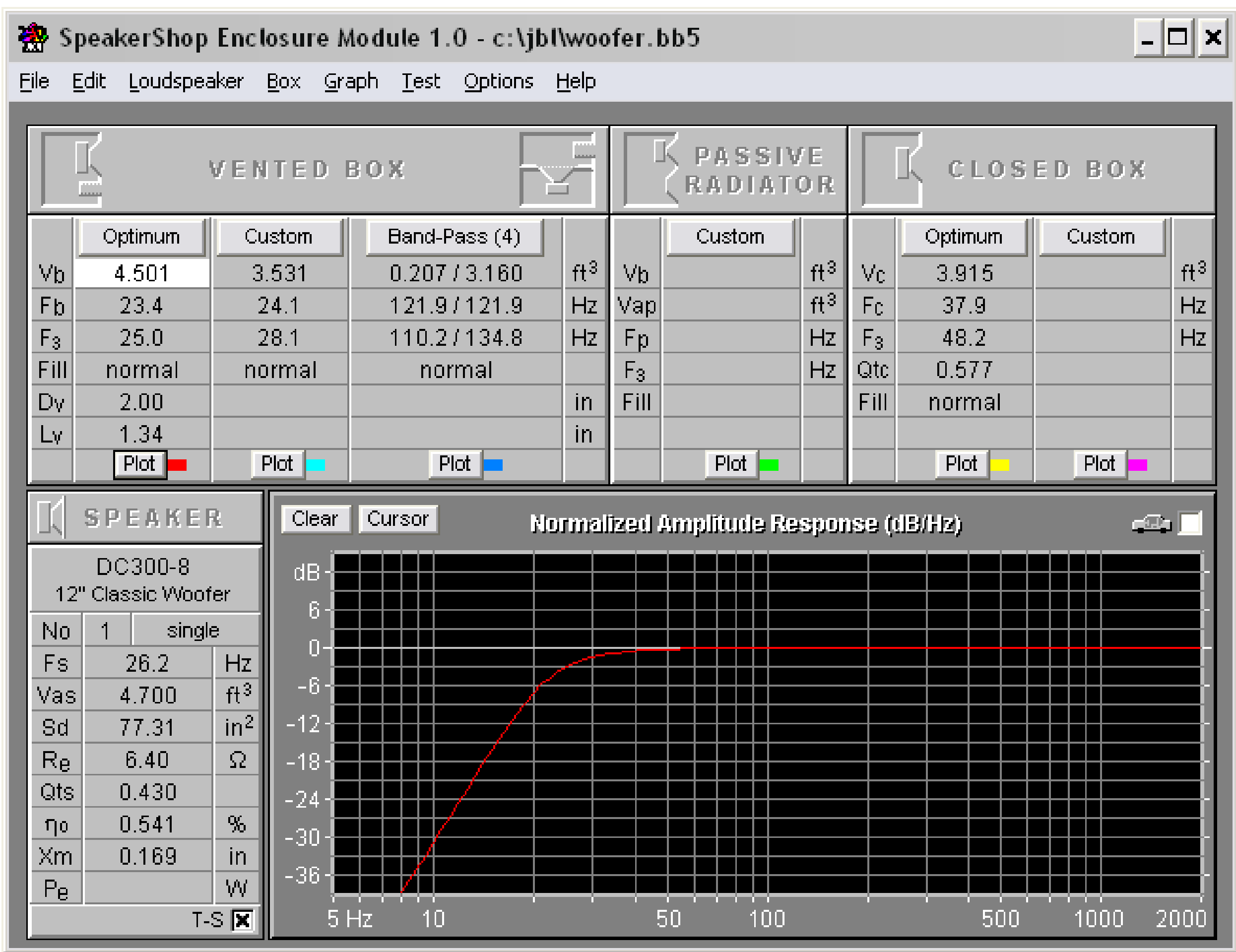
Another important role of the enclosure is to increase sound quality and sound levels by offering each driver the ideal working environment; by tuning the cabinet to a resonant frequency, and offering the driver an ideal volume to work with. In my case, since I’m working with 3 drivers, they each need to have their optimal work environments, so designing an enclosure that could take account of each drivers optimal working environment was a challenge.

i. Designing the optimum *Woofer* enclosure

Using the Thiele-Small parameters of my selected woofer, as well as computer software, it is possible to simulate the performance of the woofer in a variety of different enclosures of all shapes and sizes. This gives me a great advantage, as I can replicate and preview the performance of an enclosure before even building it, allowing me to try out different possibilities of enclosures, with the ultimate goal of finding the optimal enclosure for my woofer.

Using the *JBL SpeakerShop Enclosure Module* software, the optimal internal volume was determined to be 4.5 ft^3, in a vented type enclosure, with a single 2" diameter vent. This enclosure gave the woofer a neat +3dB gain below 50Hz, which is a significant gain. The combination of the tuned resonant enclosure with the optimal working volume gave this enclosure and woofer a significant increase in performance, compared to other types of enclosures.

The following screen capture from the *JBL SpeakerShop Enclosure Module,* and shows the simulated frequency response for the vented enclosure that I decided to build. The lower left hand side shows the drivers Thiele-Small parameters, with the upper left hand site displaying the enclosure characteristics. Full screen capture for this enclosure simulation can be found in ***Annex 3***.

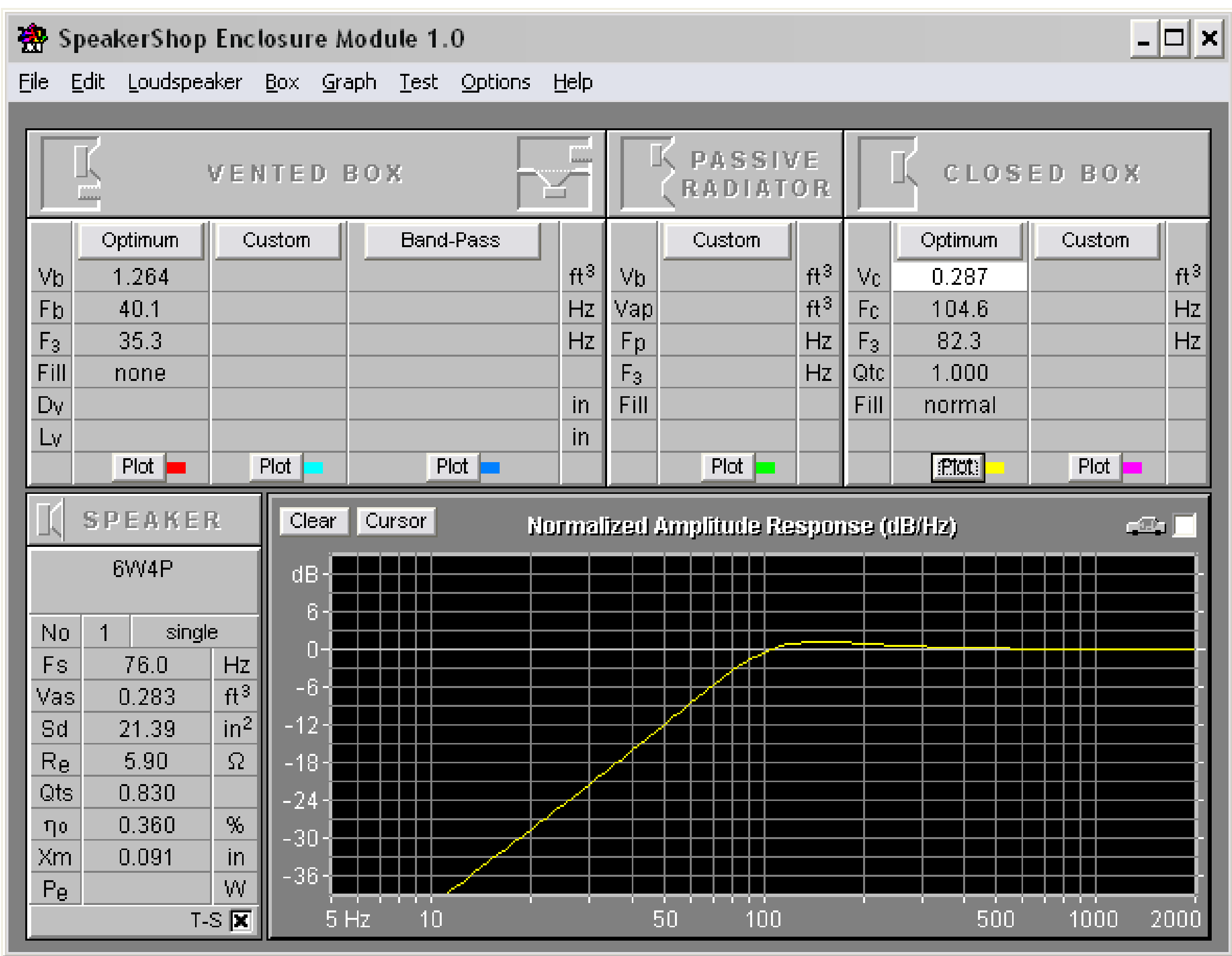


ii. Designing the optimum *Mid-Range* enclosure

Using the same method and software used to determine the woofer enclosure, the mid-range driver has to be isolated as well into its own enclosure. That being said, we are basically building two different enclosures, one for the Woofer, and another for the mid-range.

One reason for this is that the mid-range uses a sealed enclosure, as there is no advantage in tuning the box for the frequency range in which this driver operates. As well, the mid-range driver has to be isolated from the woofer, as the amount of air displaced by the woofer when operating could potentially disrupt the free movement of the mid-range.

The following screen capture from the *JBL SpeakerShop Enclosure Module,* and shows the simulated frequency response for the sealed enclosure for the mid-range, which has an optimal volume of 0.287 ft^3. Full screen capture for this simulation can be found in ***Annex 3***.



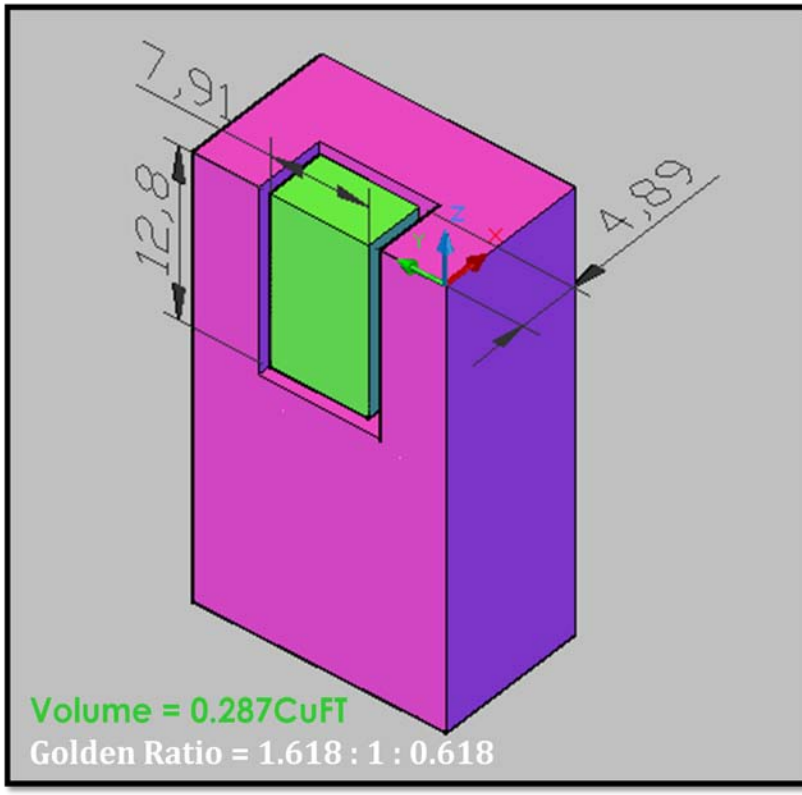
iii. Designing a combined enclosure

Now that I've computer the optimal parameters for each loudspeaker, it is time to combine them together into one enclosure. The objective is to integrate the mid-range cabinet into the woofer cabinet, so from the outside everything appears as one whole enclosure. As for the tweeter, this driver is already an isolated component, so it does not need its own enclosure and will be put with the mid-range.

As well as designing a cabinet that will house the 3 drivers and keep the correct internal volumes, the dimensions of the enclosure will all correspond to the Golden Ratio. The Golden Ratio refers to the ideal ratio for height, width, and depth of a speaker enclosure to reduce internal standing waves which is 0.6: 1.0: 1.6. The details are very mathematically specific and have to do with sound wavelengths in relation to the lengths of the internal walls of a speaker cabinet. Regardless, if you have a speaker cabinet that follows the 'Golden Ratio', internal standing waves will be greatly diminished.

Using the *JBL SpeakerShop Enclosure Module* to calculate some of the internal dimensions, as well as some thought out calculations to keep the internal volume intact, I was able to design an enclosure that respected all of my conditions, keeping the internal volumes intact, and following the Golden Ratio for the cabinet construction.

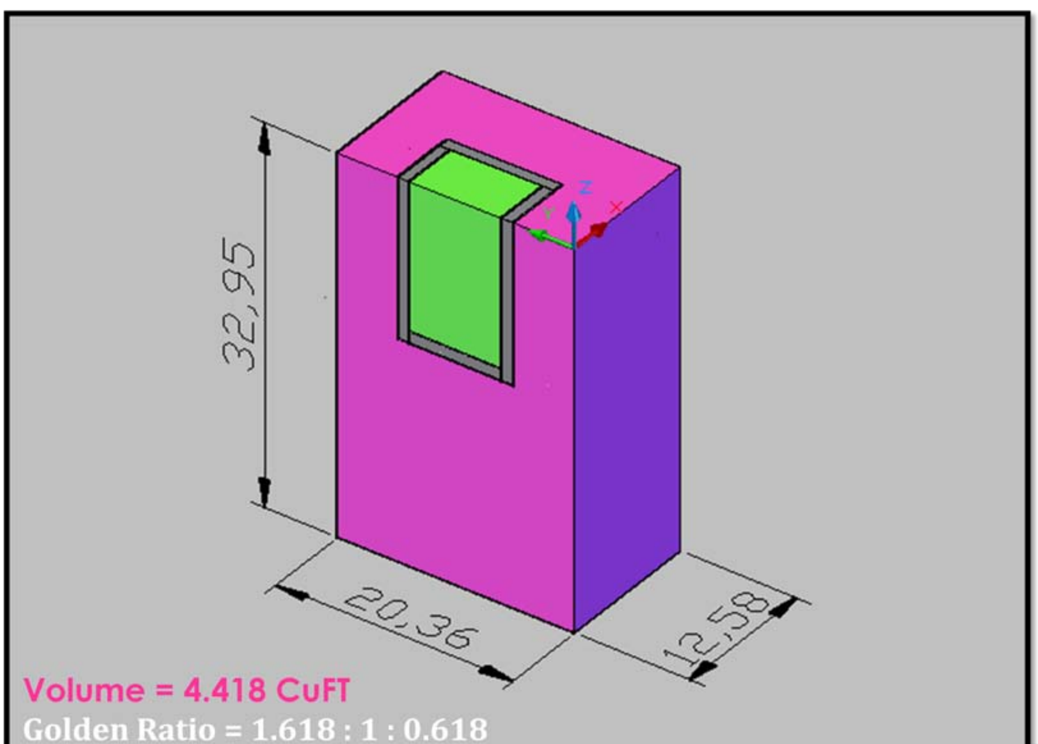
Before the build began, I modeled the cabinets in *AutoCAD 2008*, which gave me a clear perceptual view of what the final product would resemble. The enclosure was designed to be both aesthetically pleasing, offering a recessed edge, and to have the performance characteristics required to offer each driver its ideal working environment.



The *AutoCAD 2008* renders of the cabinets clearly show in the internal volumes of enclosure, purple being the woofer and green being the mid-range. As well, we can see that the Golden Ratio has been respected throughout the enclosure.

The enclosure its self was built as a "shell" around the internal volumes, ensuring that they would stay intact. Once the outer shell was modeled, the measurements were marked down and I started working with 5 x 8 sheets of MDF to get all of the pieces I required for building two of these cabinets cut out.

*The full page schematics for the internal enclosure, as well as the external shell can be found in **Annex 3**.*



iv. Internal damping, epoxy covering & final assembly

Now that the enclosures are assembled, some internal damping was needed to help absorb some of the sound and reduce the reflection of sounds waves off the internal cabinet walls. For damping, a material made of recycled textile, often found in mattresses, was inserted and secured to the box walls. This seemed suitable for my application, as it was of a decent thickness and should improve the characteristics of the enclosure.

As well, once all sealed up, it was time to finish the MDF enclosure. For my project, it was decided that an epoxy based finish should be applied, as it has great elastomeric properties which would make the enclosure rugged and durable to any abuse it might take down the road. At first using paint was considered, but the MDF scuffs too easily, and any abuse would have quickly shown up on the enclosure. The epoxy coating applied gives the enclosure a nice rugged looks, and can take quite a beating while keeping the internals intact. This was a compromise between finishing the MDF with a stain or veneer, which would render it less rugged but perhaps more suitable for an indoor application, or making it a versatile indoor/outdoor speaker which could take a good beating or two.

The final assembly of the cabinets compromised securing in the drivers using tee-nuts to prevent the nuts from falling in the enclosure if ever the speakers removed, assembling the handles and rear input plate using tee-nuts as well, and securing the connections to the rear plate.

Once fully assembled, the cabinets were tested to ensure all the connections were secured and that all the components were tightly in place. This concludes the theoretical and work sections of the report.

Data & Analysis

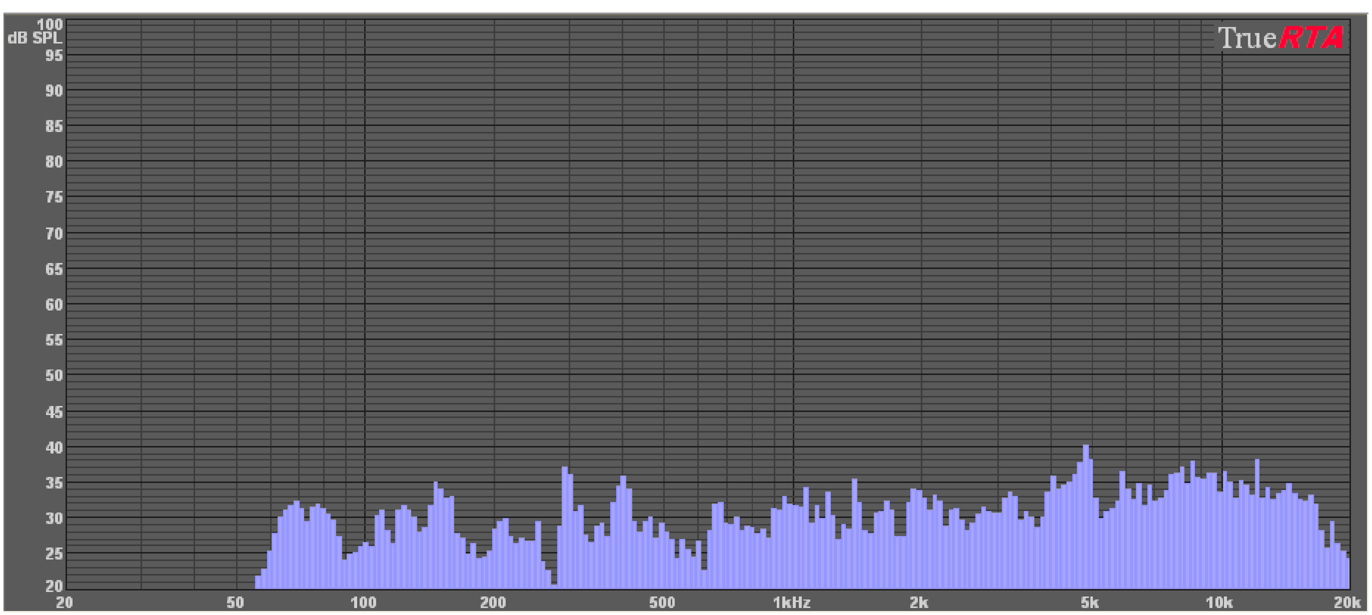
The performance of loudspeakers can be determined by their frequency response, and their ability to keep a constant SPL throughout the range of frequencies played by these speakers.

One test that loudspeakers are often subjected to is to have them play “white noise”, which is a signal that contains equal power within a fixed bandwidth at any center frequency. The idea is that the white noise played out by the speakers will be picked up by a microphone, and then analyzed with computer software to see if there are any inconsistencies in the SPL, either gains or losses, throughout the frequency range.

Although I tried replicating this setup using a CD loaded with a white noise soundtrack, and a professional Samson condenser microphone hooked into my laptop via an M-Audio Preamp, there are many variables such as the room type and dimensions which have an inevitable effect on the perceived performance.

Ideally, the frequency response is recorded in an anechoic chamber using professional equipment and a white noise generator, but even then there are sources of errors that cannot be avoided.

Here are the results of the “white noise” test, using the equipment described above, recorded at my residence, in a room of about 20ftx10ft.



Discussion

When it comes into the mechanics of loudspeakers and trying to reach the best frequency response possible, there is just no end to the complex theoretical and sometimes “voodoo” magic needed to obtain the perfect loudspeaker. What it comes down to in the end is the audible perception of the loudspeaker, which either sounds “good” or “bad”. This is where loudspeakers become a nuisance, because to the average consumer, good loudspeaker performance is perceived to be a speaker which is “loud with lots of bass”. To the trained ear however, equilibrium of all frequencies and a realistic reproduction of sound is what is really wanted in any loudspeaker.

A smart manufacturer will give the consumer exactly what they want, by going against the conventional rules of loudspeaker design, and forcefully “flawing” the design to have a higher low frequency SPL. Although this loudspeaker doesn’t realistically replicate the recorded source, it does offer a pleasing atmosphere in night clubs and other venues which rattle the ceiling with incredible loudness.

I was aiming for a realistic reproduction of sound with a constant SPL, and that is what I obtained. I am glad with the final results of my project, on both aspects of the actual speaker cabinet’s look and construction, as well as its performance, which was measured as accurate as possible with the equipment at hand.

The most time consuming portion of the project was the construction of the loudspeaker cabinet, which included designing the cabinet, cutting the MDF and assembling it together. Little time was lost waiting for the construction glue to set, as I would work on other task while that was setting.

I am glad that I purchased the drivers within the first couple weeks, as the electronics and enclosure were put on a hold until I could gather the Thiele-Small parameters from the speakers and put it all together.

I did encounter a problem using the epoxy coating, as on the second batch that I mixed together, not enough hardener was introduced into the mix, which caused a different textured finish, as well as a tacky surface. However, this was quickly fixed with some clear coat, and an extra layer of epoxy on the front surface, which immediately brought back the correct surface texture. As well, the back baffles of each speaker were painted a flat black, as I only had enough epoxy left over to cover one of the speakers. The flat black finish resembles the rest of the enclosure, and is hard to notice unless up-close to the whole cabinet. I'm not worried about the cabinet getting damaged where there is a lack of epoxy, since it is only the recessed baffle.

The issue with not finding the exact value components did have me worried, but I was limited to whatever parts were available on the market so had to make quick and find suitable replacements for the nonexistent component values I had calculated. The values I found were within reasonable limits to what I had calculated, and ended up not being an issue at all.

The overall project ended up costing more than anticipated. What threw me off budget was the high price of the 1" MDF, at about 50$ a sheet, for a total of 2 sheets at 100$. As well, the inductors that I needed had a fairly high inductance, and I could only find them from Solen in St-Hubert, which rang me up about 25$ per inductor, with a total of 4 inductors for 100$. The whole project ended up costing me around 500$, which includes everything from drivers, enclosure, hardware & electronics. Had these speakers been purchased in store, they could have rung me up an easy 1000$+, due to the sturdiness of the enclosure, custom finishing, and fine tuning of each driver.

Overall, I'm exceedingly pleased with the final result of the project, and I'm looking forward to many years of showing off these custom loudspeakers with impressive sound quality.

Conclusion

To conclude, I believe I have successfully completed the mandate of the Project 1 course, which was to utilize the knowledge gained from the first 4 semesters in selecting, developing and implementing a project related to the applied physics component.

I believe after having completed this project, I have achieved the capacity to develop and implement a project, demonstrated project management and time management skills, and have been able to demonstrate the results to the department in the form of both oral and written presentations.

This project involved many aspects that related to the fields of electronics and audio, allowing me to apply the knowledge that I've acquired during my three years in the Engineering Technologies program, as well as profound my knowledge of audio systems and the complex theory behind them.

This project was a rewarding and instructive method to practically apply the theory and knowledge I've acquired, and I'm glad to see the final results that my perseverance throughout the last 15 weeks has given me.

Recommendations

One of the main recommendations I have to note if ever this project is to be attempted again is to ensure that time is allocated for unforeseen problems which can, and probably will, occur. Thankfully, I had set aside about 15 hrs, 1 hour/week, to count for unforeseen problems or for task taking longer than expected. I ended up using theses 15 hours, and a little more, as certain task took longer than expected. So, for the next project, I know to plan ahead for unexpected issues or delays that can occur.

On a technical note, I would as well recommend that both enclosures be covered with the epoxy at the same time, using the same mixtures, as the slightest change in mixing ratios can have a great affect on the finish. Thankfully, I was able to correct this problem thanks to proper planning for unforeseen events.

I would recommend as well that the purchase of all components that require international shipping be done ahead of time, as delays due to the weather or holdings at customs can greatly delay the delivery of a package.

References

The following websites were consulted:

http://www.diyaudioandvideo.com/
http://www.diyaudio.com
http://www.norh.com/
http://www.the12volt.com/
http://web.telia.com/~u87124019/softwares.html
http://www.madisound.com
http://en.wikipedia.org
http://www.loudspeakers.ca/
http://tubesall.hihome.com/speaker.htm
http://thespeakerguys.blogspot.com
http://www.thielesmall.com/
http://www.partsexpress.com/
http://audiokarma.org/
http://diyaudioprojects.com/
http://home.earthlink.net/~etunstal/diy.htm

The following books were consulted:

Dickason, Vance. “Loudspeaker Design Cookbook”. 7th Edition. 295 Pages. ISBN: 1882580478.

Annex 1

Manufacturer specification sheets

&

Frequency Response graphs

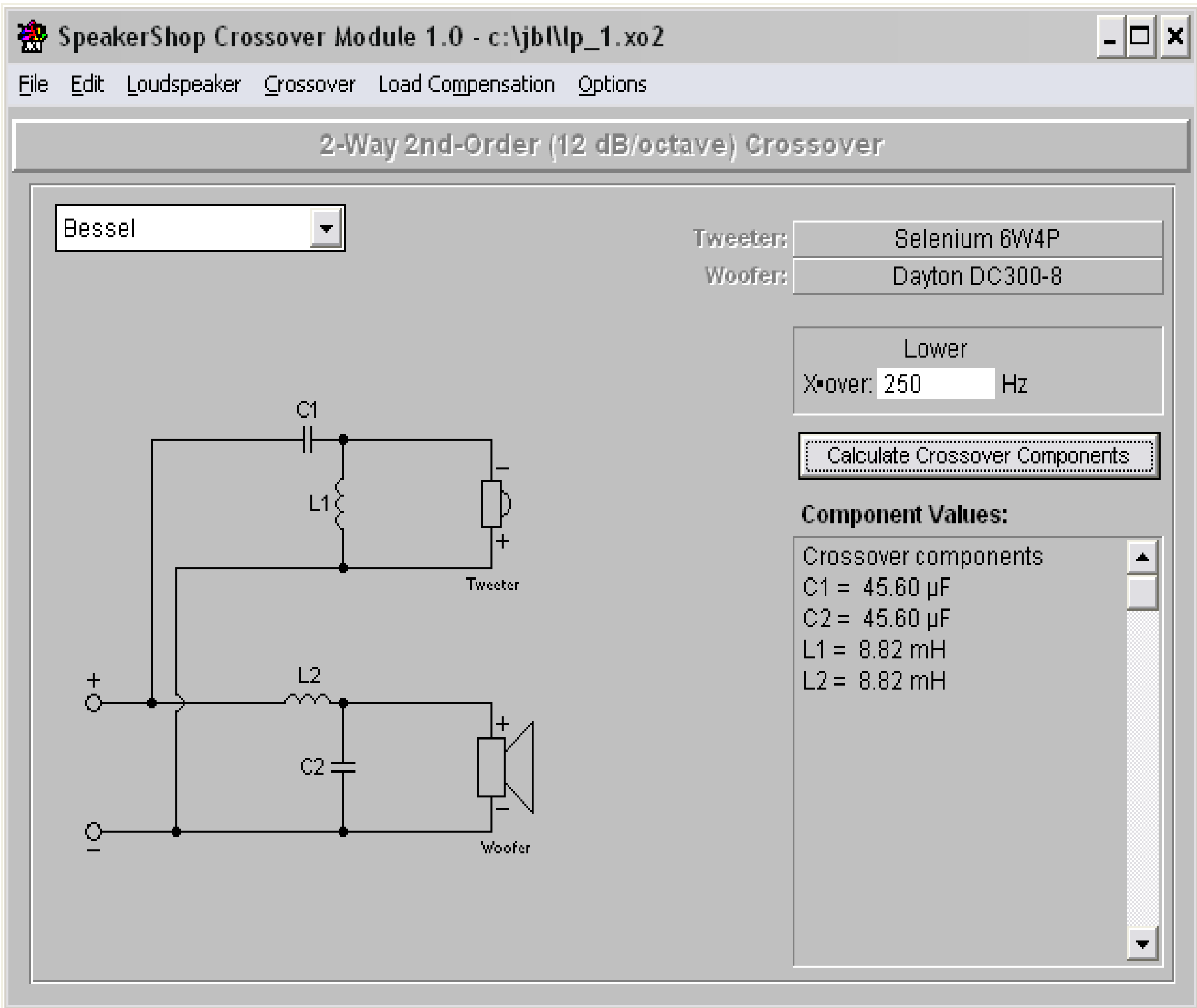
Annex 2

JBL SpeakerShop Crossover Module Simulations

&

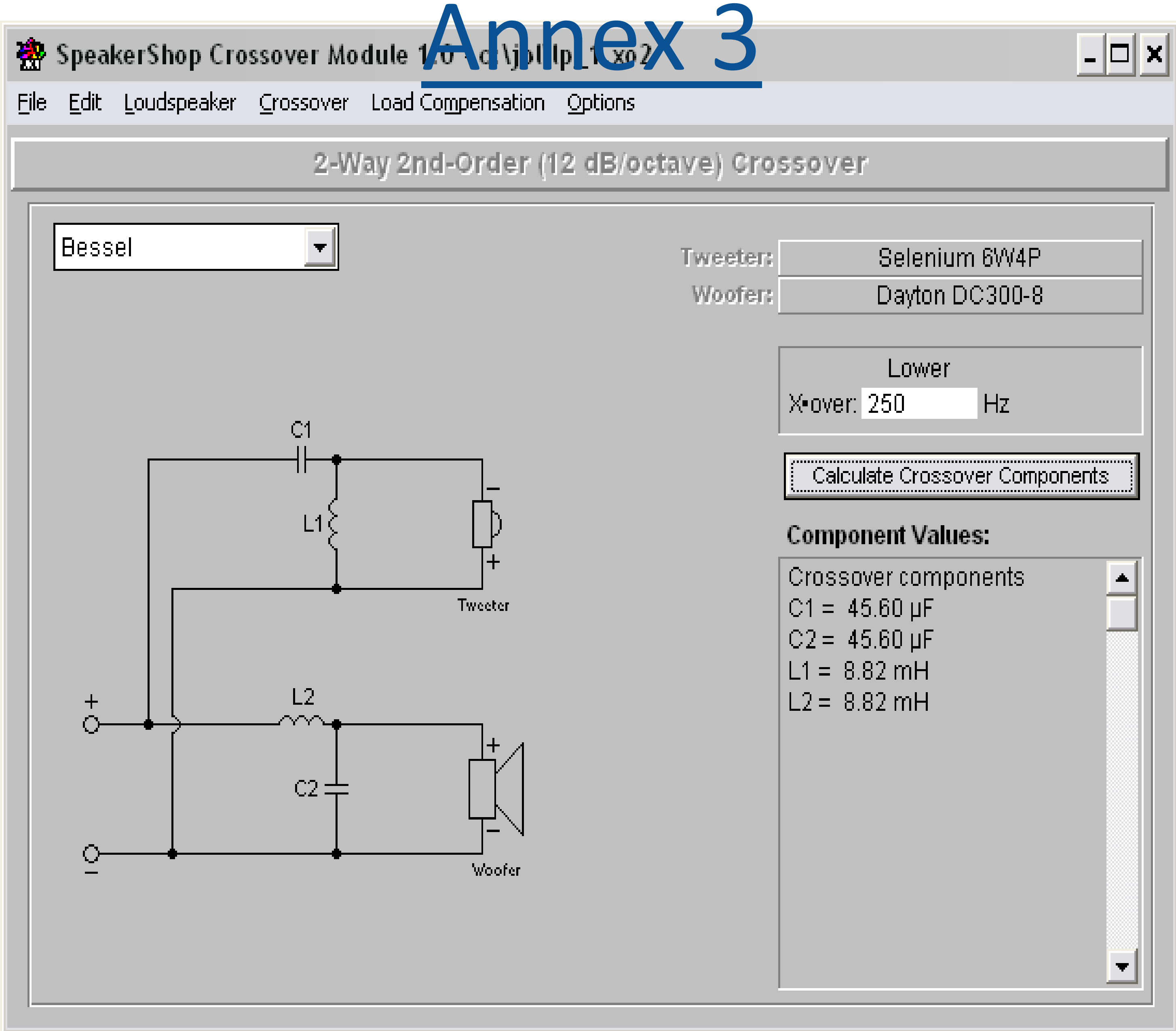
Electronic Workbench (EWB 6) Simulations

Bessel 2^{nd} Order Filter Simulation
Mid-Range & Tweeter



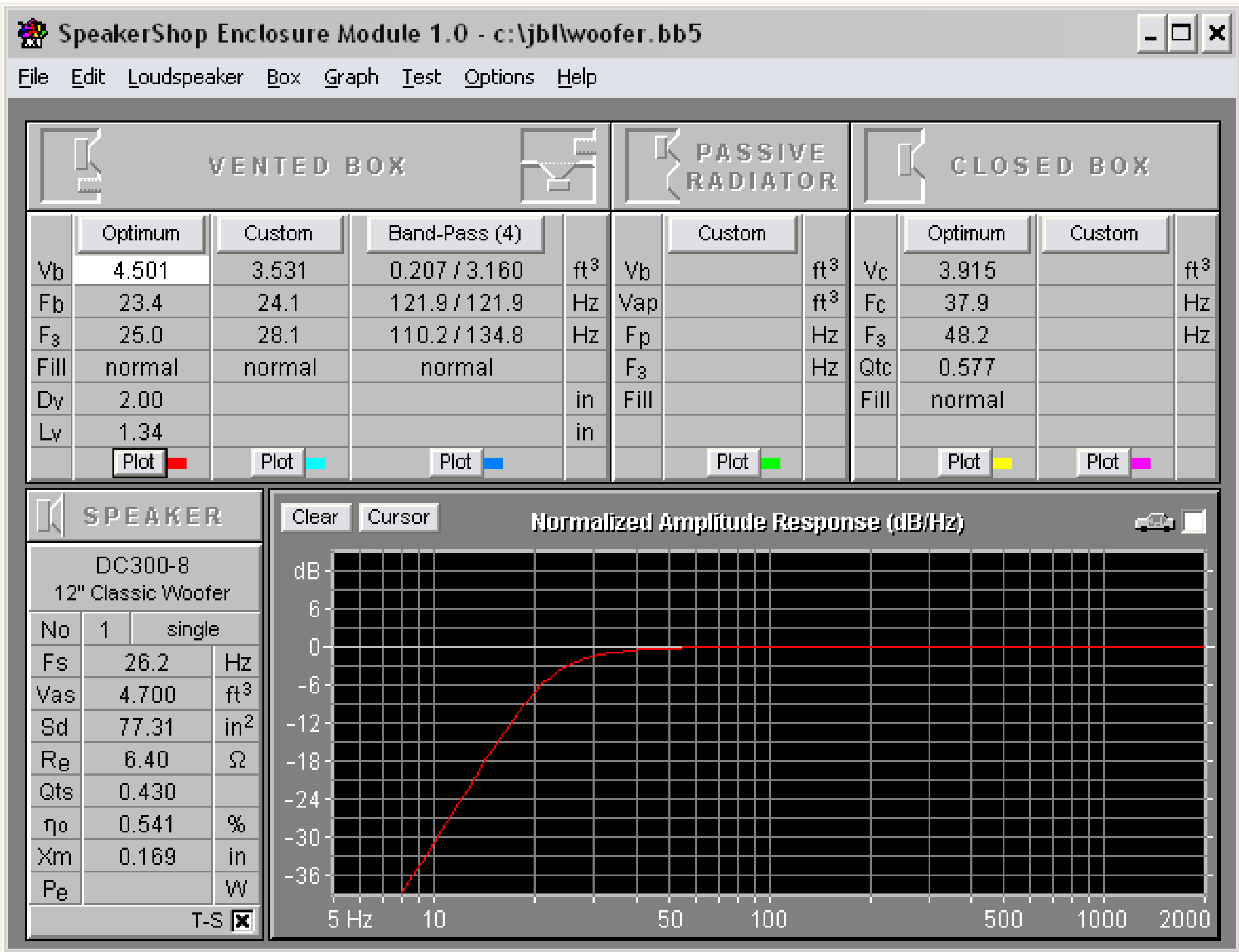
Bessel 2nd Order Filter Simulation
Woofer & Mid-Range

Annex 3

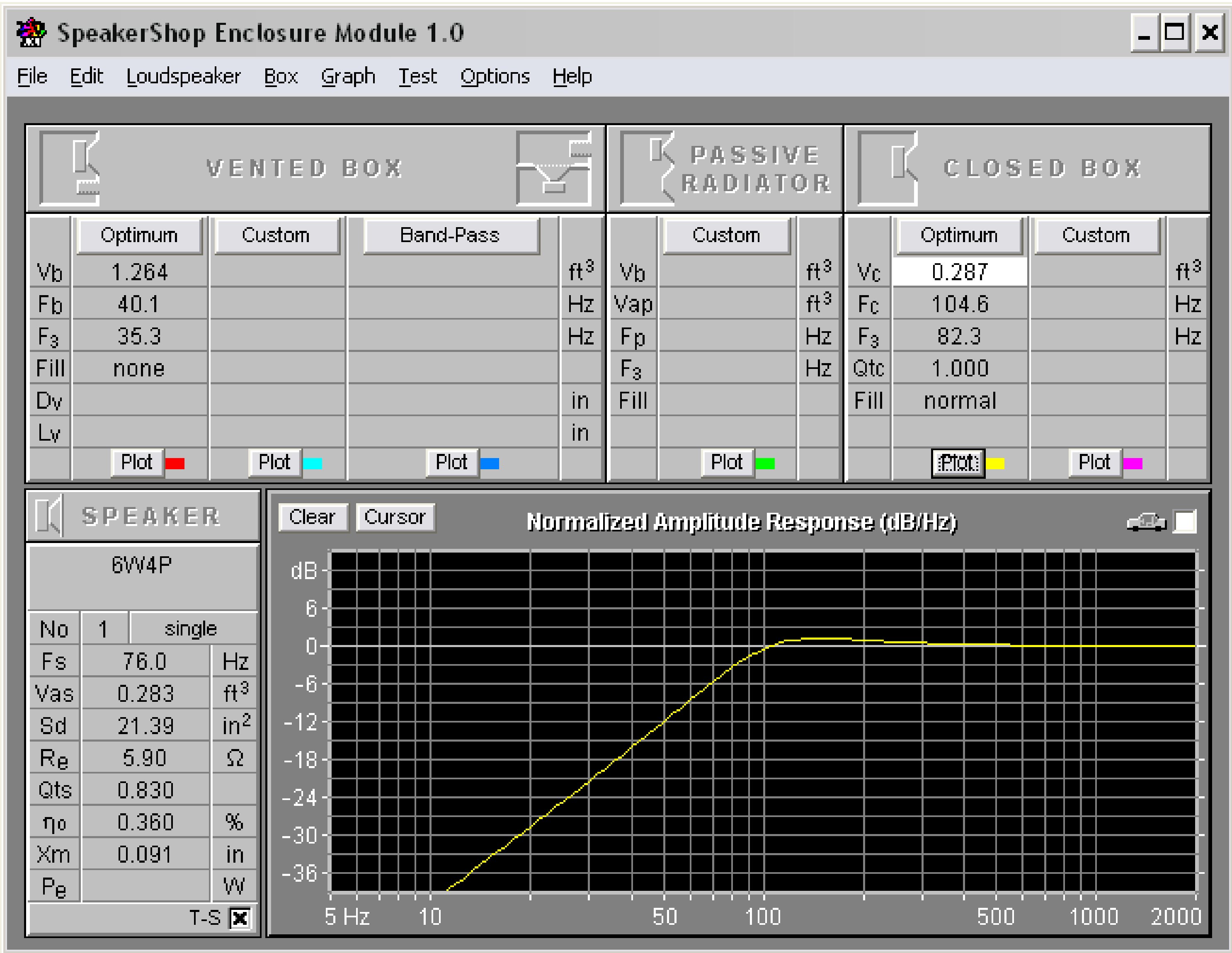


JBL SpeakerShop Enclosure Module Simulations
&
AutoCAD 2008 Renderings
&
TrueRTA Spectrum Analysis Graphs

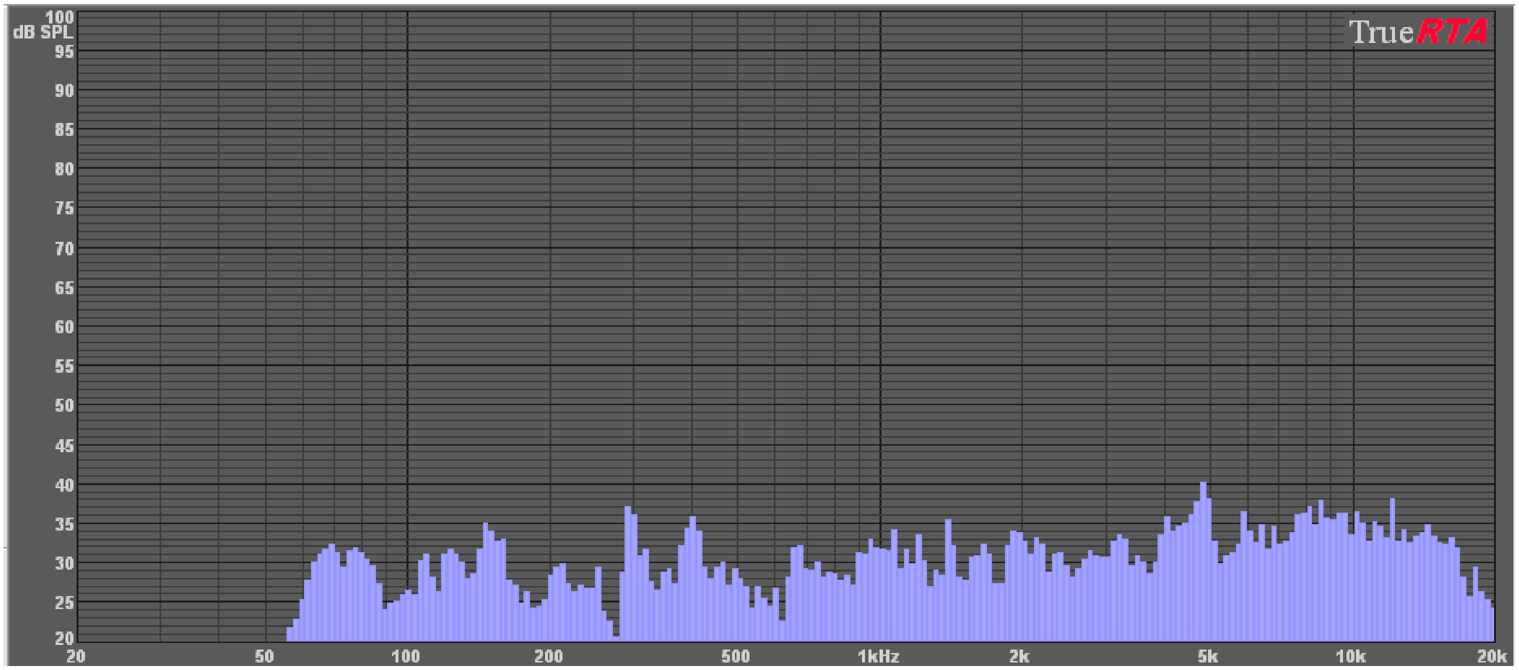
SpeakerShop Enclosure Module Simulation
Woofer Enclosure

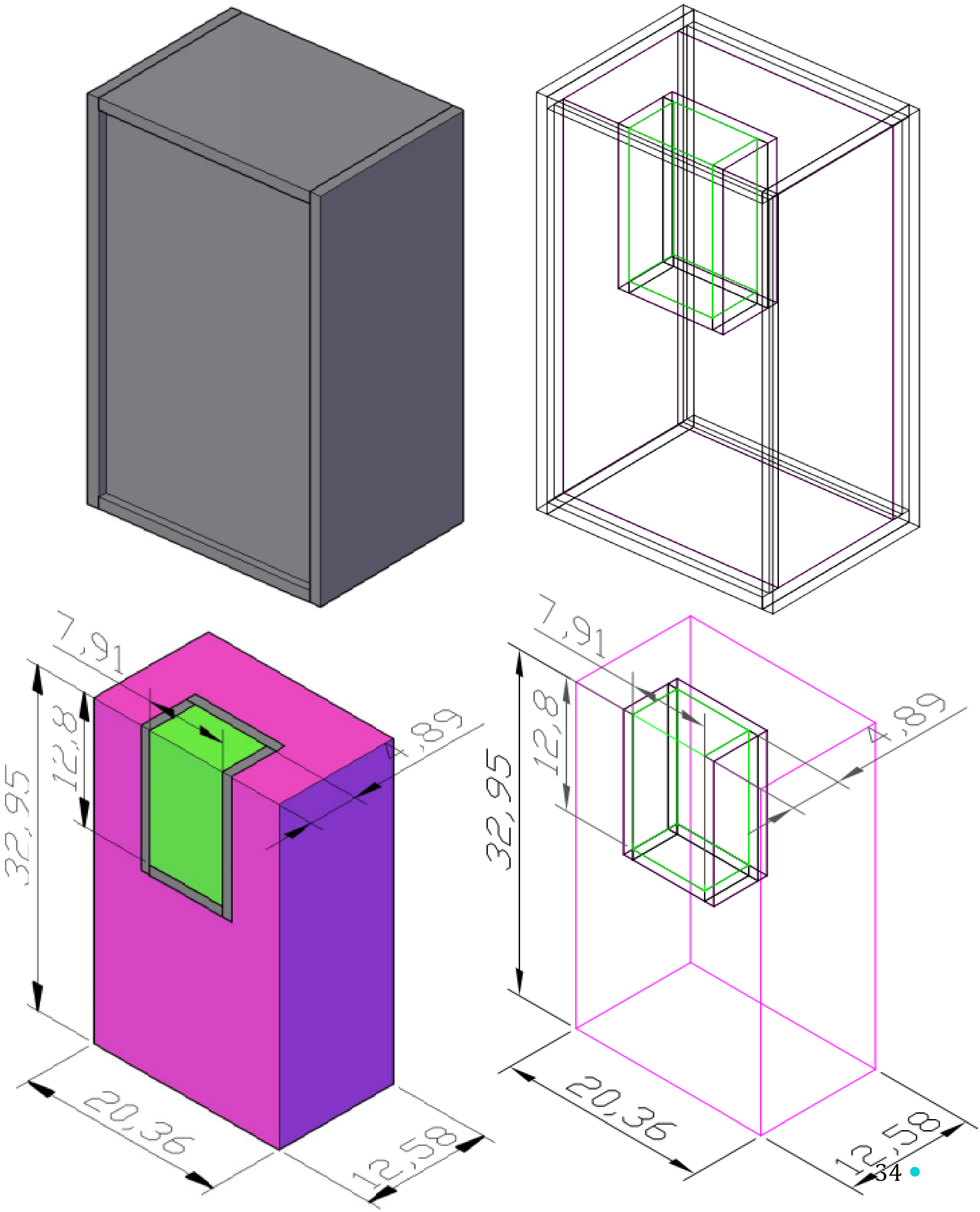

SpeakerShop Enclosure Module 1.0 - c:\jbl\woofer.bb5
File Edit Loudspeaker Box Graph Test Options Help
VENTED BOX
PASSIVE RADIATOR
CLOSED BOX
Optimum
Custom
Band-Pass (4)
Vb 4.501 3.531 0.207 / 3.160 ft3
Fb 23.4 24.1 121.9 / 121.9 Hz
F3 25.0 28.1 110.2 / 134.8 Hz
Fill normal normal normal
Dv 2.00 in
Lv 1.34 in
Plot
Vb ft3
Vap ft3
Fp Hz
F3 Hz
Fill
Vc 3.915 ft3
Fc 37.9 Hz
F3 48.2 Hz
Qtc 0.577
Fill normal
SPEAKER
DC300-8
12" Classic Woofer
No 1 single
Fs 26.2 Hz
Vas 4.700 ft3
Sd 77.31 in2
Re 6.40 Ω
Qts 0.430
ηo 0.541 %
Xm 0.169 in
Pe W
T-S
Clear
Cursor
Normalized Amplitude Response (dB/Hz)
dB
6
0
-6
-12
-18
-24
-30
-36
5 Hz
10
50
100
500
1000
2000

SpeakerShop Enclosure Module Simulation
Mid-Range Enclosure



TrueRTA Real-Time Spectrum Analysis
White Noise @ 5ft distance w/ condenser microphone





All units are in Inches