Satori MTM Bass Reflex Speaker System

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Introduction :

Late last year I decided I wanted to build a traditional two way speaker system. I have been working almost exclusively with full range drivers for the past 10 years and decided that the challenges associated with designing a speaker system with a box, woofer, tweeter, and associated crossover was something to get back into again. But before I dig in to this design, let me make a few general observations about multi-way and full range driver enthusiasts.

When working with full range drivers, designing an enclosure to reinforce the low frequencies is the major challenge. The mid-range and high frequencies are all produced by the full range driver and there is not much other than some passive EQ that you can do with the top end (although the purists won't accept even the thought of any passive network between the amp and the driver). The full range driver builder spends an enormous amount of time with exotic enclosure designs that try and coax some decent bass from a driver with a rolling off low end frequency response and a small X_{max} value. If you are a purist full range driver user then the enclosure is probably some form of back loaded horn (single or double mouthed) that mixes TL response at the very lowest frequencies transitioning to horn loading as frequency rises. The design of acoustically tuned enclosures for low frequency sound reproduction is the main strength of this DIY speaker building group.

The two way builder in general sticks to more common sealed or bass reflex enclosure designs. There are a few TL and ML TL designers but the majority of the builds would fit under the category often referred to as monkey coffins. The focus and effort of multi-way speaker builders is the crossover design. The box gets a quick once over using one of the lumped parameter simulation programs and then the fun begins with the crossover design. There are free software tools available for designing passive crossovers that are extremely sophisticated and have taken many hours to program and debug. These programs can read in the measured response of individual drivers mounted on the box's baffle and then allow the user to go way beyond traditional text book filter theory to design very effective circuits that smoothly transition from one driver to the other. Crossover design and system integration is probably the strongest skill set represented in this group of DIY speaker builders.

I am not trying to offend anybody, or pass judgment on which approach is better, but if you look at the posts on the Parts Express forums and compare them to posts on the DIYaudio full range forum I think the generalizations I have made above are proven out. It is also interesting to note that there are not many common names among the posters on these two forums, there is minimal cross pollination of design ideas. While my statements are quite general, and there are always exceptions, I think they accurately summarize the division between these two groups of speaker building hobbyists.

Having spent many years with full range drivers reverse engineering all of the back loaded horn designs I could find on the Internet I began to think about a two way woofer and tweeter system and what kind of non-traditional box designs would be possible. The current MathCad worksheets do a great job on TLs and back loaded horns up to 1 kHz but lack the second driver and crossover design features. As a result, a fairly extensive upgrade of several MathCad worksheets took place and then I was ready to shift back over to the dark side and start work on a two way speaker design.

MathCad Upgrades :

My goal with the MathCad worksheets was to completely design the speaker system and gain confidence in the design before spending anything on drivers, crossover parts, or wood. This means I needed to simulate the woofer and the tweeter on the front baffle, the crossover circuit, and the enclosure combined with nearby room boundaries to calculate a system SPL response over the frequency range 10 Hz to 10 kHz. Calculating a SPL curve will not tell you how a speaker will sound, however if you can reference a SPL response curve for a speaker design you like and dial in something close you will have some initial insight into how the finished system will perform. Having a reference SPL response curve also allows you to tweak the design to change the performance and adjust to meet your own personal taste in sound or compensate for a property of your listening room.

The upgrades to the MathCad worksheets included extending the enclosure modeling capability beyond the current 1 kHz limit up to 10 kHz. The fiber stuffing correlation needed to be adjusted and the numerical solution for the open end acoustic impedance extended. Next the passive crossover sections of the OB worksheets were inserted and upgrade to include more circuit elements in each leg and a capability to include Zobels, L-Pads, a BSC filter, and a parallel or series trap for each driver. The passive crossover options programmed include both parallel and series configurations.

Modeling the woofer was fairly straight forward using the T/S parameters. However T/S parameters are not typically available for the tweeter and how to measure them is not so obvious. Hooking a computer measurement system, like my Praxis set-up, to a tweeter allowed me to carefully generate an electrical impedance curve where it was straight forward to determine f_d, R_e, Q_{ed}, Q_{md}, and Q_{td}, and then measure the diameter by hand to calculate S_d. The missing parameters are BL and V_{ad} which are used to calculate the SPL/W/m. For a tweeter the added mass and the closed volume methods for determining the missing parameters are out of the question. But knowing SPL/W/m or SPL/2.83 volt/m allowed me to back out BL and V_{ad}. A complete set of T/S parameters for the tweeter was not too difficult to determine from an impedance curve and a SPL value referenced to 1 watt or 2.83 volts.

After this upgrade the MathCad worksheets were able to simulate a two way speaker in an enclosure, with a crossover, and placed in a room with nearby floor, ceiling, and wall boundary conditions. This was all done in one pass and the results were predictions for electrical impedance, directional SPL response at a specified location, and vertical and horizontal polar plots of SPL at specified frequencies. What is not included is any driver break up or non T/S response. It was now time to select some drivers.

Driver Selection :

While I was busy upgrading the MathCad worksheets I started to accumulate a list of potential mid-bass woofers and tweeters for a two way system. Drivers ended up on the list based on DIY designs found on the Internet that were supported by positive feedback and measurements. The number of alternatives, especially for tweeters, from Scan Speak and SEAS became overwhelming. During this time I also read a number of very positive comments on the SB Acoustics Satori line of drivers. I really liked what I saw in the manufacturer's data sheets and the close correlation with a few independent measurements of impedance and SPL response that I found on the Internet.

I ended up selecting the Satori MW16P-8 mid bass driver and the TW29R ring radiator tweeter. I selected the 8 ohm version of the mid-bass driver so that I could wire two in parallel and maintain an approximately 4 ohm minimum resistance. I did enough scoping using the manufacturer's datasheet to give me confidence in the selections so I went ahead and placed orders for the drivers from Madisound and Meniscus.

I used Praxis to measure the T/S parameters for all six of the Satori drivers and then averaged the results; the correlation with the manufacturer's data sheets was very good. The results were essentially drivers right out of the box with minimal break-in time. My measured T/S parameters are shown below.

	Summary of T/S Parameters for Satori MW16P Drivers					
Parameter	1	2	3	4	Units	Average
fs	31.151	32.478	31.978	31.671	Hz	31.411
Qes	0.431	0.444	0.435	0.444	-	0.438
Qms	5.354	5.360	5.598	5.582	-	5.468
Qts	0.399	0.410	0.404	0.411	-	0.405
Re	6.0	6.0	6.0	6.0	ohm	6.00
Lvc	93.38	131.40	93.90	96.43	uH	94.91
Vas	28.59	25.10	29.38	28.20	liter	28.40
BL	7.023	7.234	6.803	6.840	N-A	6.932
Sd	119.00	119.00	119.00	119.00	cm^2	119.00
Mms	18.100	18.960	16.710	17.380	gm	17.740
Cms	1.442	1.266	1.482	1.452	m m/N	1.447
SPL	84.85	84.70	85.26	84.97	dB/W/m	84.91

Summary of T/S Parameters for Satori TW29R Drivers				
Parameter	1	2	Units	Average
fs	677.314	666.113	Hz	671.714
Qes	1.421	1.329	-	1.375
Qms	2.226	2.202	-	2.214
Qts	0.867	0.829	-	0.848
Re	3.1	3.0	ohm	3.050
Lvc	17.22	16.27	uH	16.745
Vas			liter	
BL			N-A	
Sd	9.60	9.60	cm^2	9.60
Mms			gm	
Cms			m m/N	
SPL			dB/W/m	

The measured T/S parameters shown above for the TW29R tweeters are incomplete. To calculate values for Vas, BL, Mms, and Cms I assumed that the

SPL/W/m was 87.7 dB (92 dB/2.83 volts/m). The resulting calculated values for Mms and BL matched the manufacturer's data sheet closely.

Bass Reflex Enclosure Design :

I modeled a number of different enclosure designs for the two Satori woofers wired in parallel. I looked at floor standing TLs and ML TLs but in the end settled on a slightly oversized stand mounted bass reflex design. I wanted something that I could build simply while I worked on the passive crossover modeling being programming into my MathCad worksheets. In addition, I had enough wood on hand to build s small bass reflex cabinet but not enough to tackle a full height floor standing TL or ML TL enclosure. My next enclosure will be more exotic once the MathCad worksheets have been verified.

The internal dimensions of the bass reflex enclosure were 7.625 inches wide, 21.75 inches tall, and 13.125 inches deep. The port (PE Part 260-386) was centered on the rear baffle and has an inner radius of 1.3 inches and a length of 6.5 inches. The enclosure was tuned to about 35 Hz.

Calculated Response and Crossover Design :

I modeled the MTM bass reflex enclosure in MathCad as shown in Figure 1. My goal was to place the tweeted axis at ear level using a 24" stand and offset the tweeter 1 inch on the front baffle to combat ripple produced by baffle edge reflections. I calculated the response of the two woofers and the tweeter separately at a 1 m distance along with the electrical impedances. Figure 2 shows the calculated anechoic SPL response and impedance for the two woofers in the bass reflex enclosure while Figure 3 contains the same plots for the tweeter.

Figure 1 : Satori MTM Enclosure Model

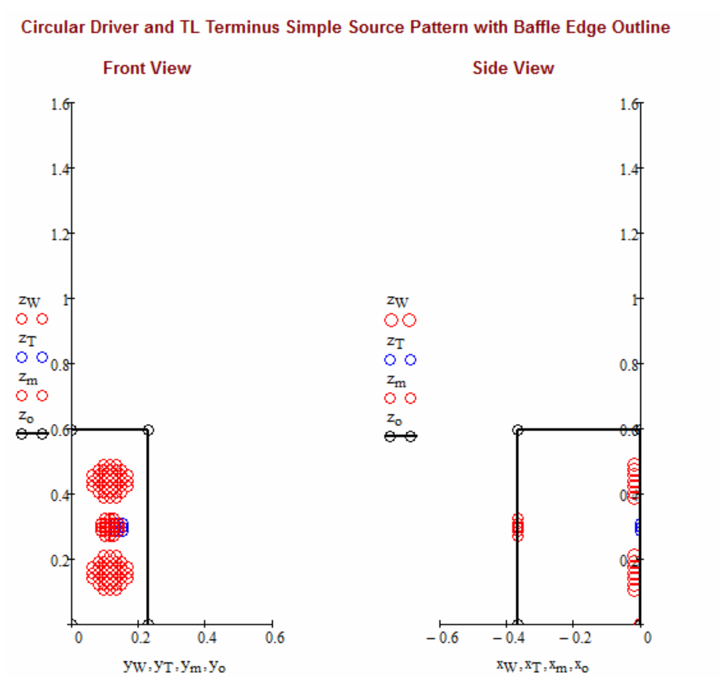
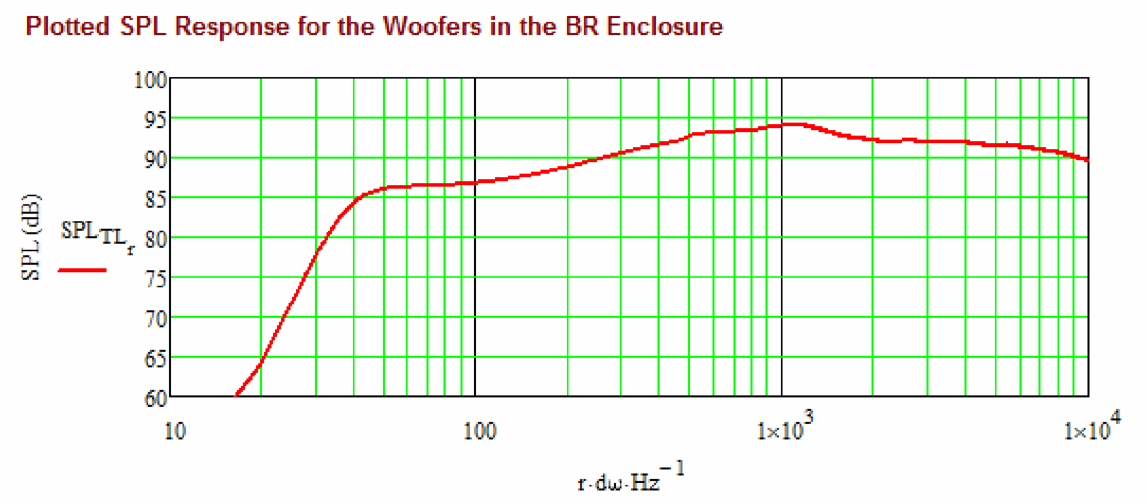
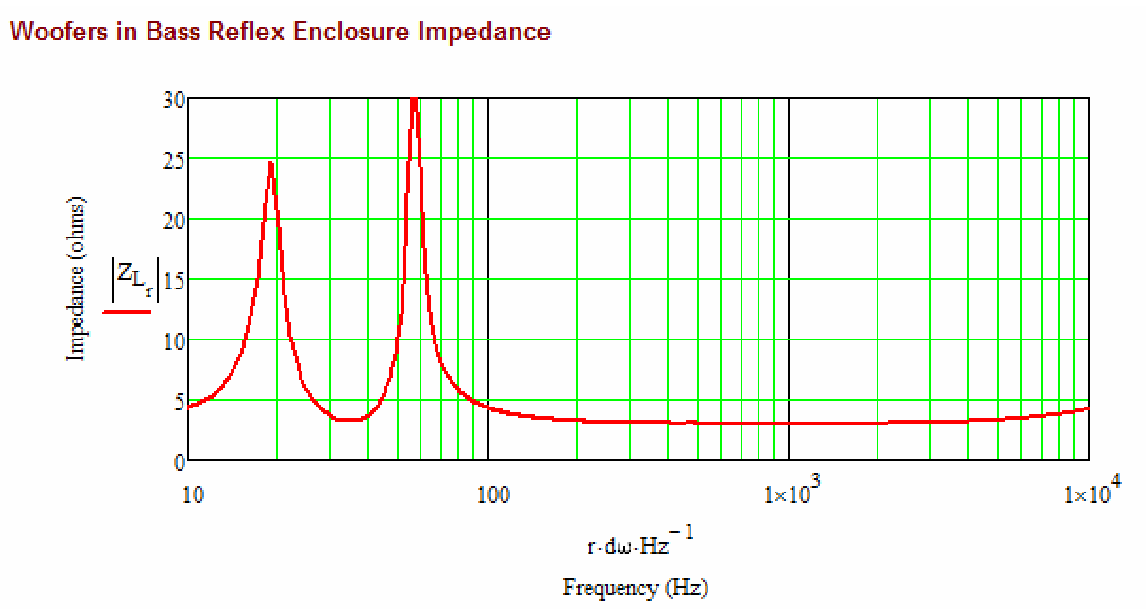


Figure 2 : Anechoic SPL Response and Impedance for the Satori Woofers

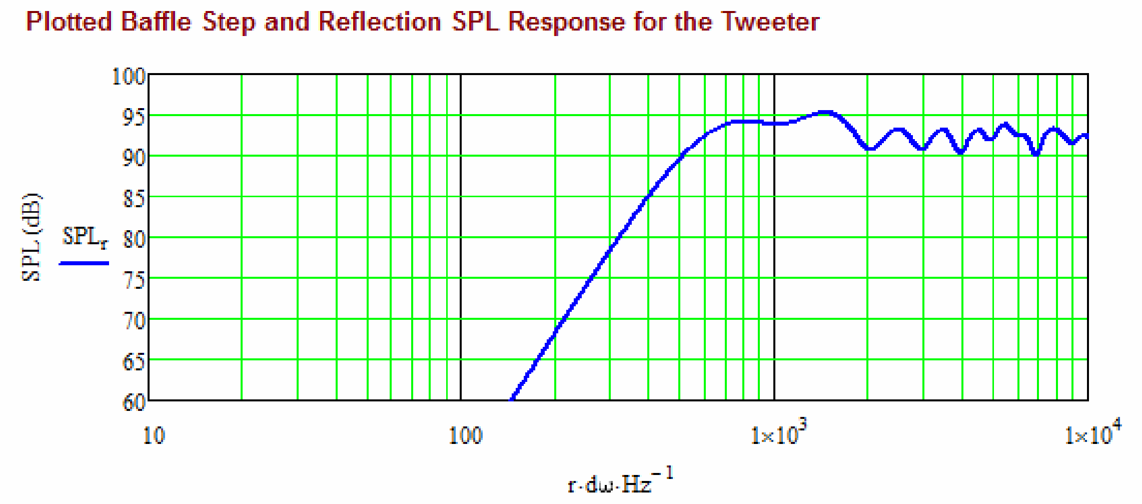


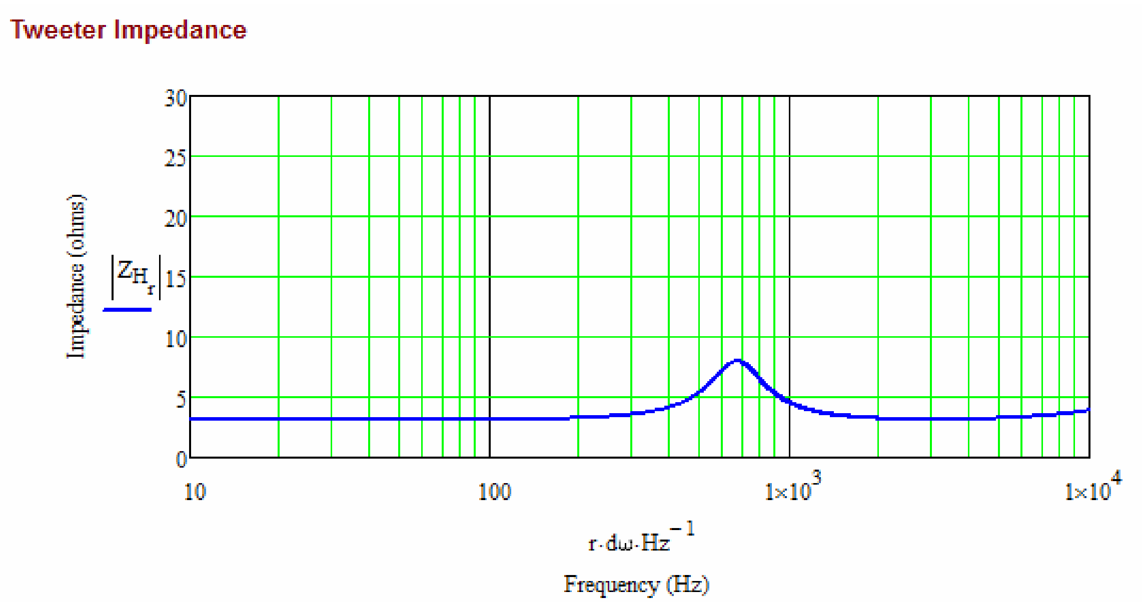


In the woofer's SPL graph the baffle step was easily seen starting at 100 Hz and peaking at 1 kHz. Based on the low frequency response the entitlement for SPL was between 86 and 87 dB/2.83 volts/m for the pair of woofers wired in parallel. Eventually the tweeter needed to be padded down to meet the SPL of the woofers below 100 Hz. The crossover also needed to address the baffle step shown in the plot.

The impedance plot showed the tuning frequency, the minimum point between the two low frequency peaks, to be at approximately 35 Hz as expected. The voice coil inductance did not seem to be a major concern so a Zobel circuit across the woofers was not necessarily required. The minimum impedance was approximately 3.5 ohms.

Figure 3 : Anechoic SPL Response and Impedance for the Satori Tweeter



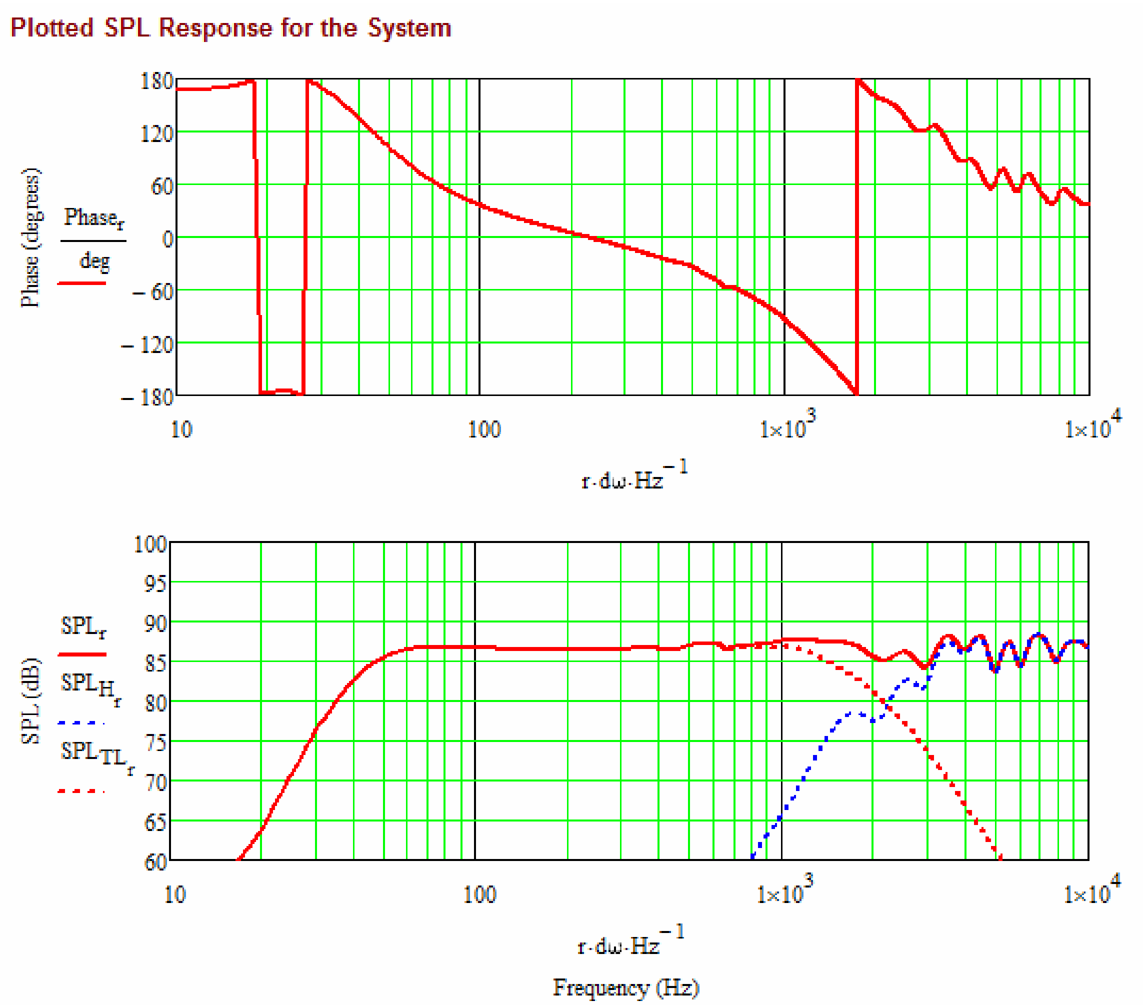


The SPL generated by the tweeter for a 2.83 volt input at a 1 meter distance was between 92 and 93 dB. The tweeter needed to be padded down about 5 dB to match the pair of woofers wired in parallel. The broad hump centered at 1 kHz and the +/- 1.5 dB ripple were the result of placing the tweeter on the front baffle, if it were not offset and centered the ripple would be +/- 2.5 dB.

The tweeter's impedance plot showed the driver resonance just above 650 Hz, which definitely interacts with the high pass crossover circuit. The DC resistances of the two woofers in parallel and the tweeter were both in the 3 to 4 ohm range. These low resistances helped reduce the values of some of the crossover parts which in turn reduced cost.

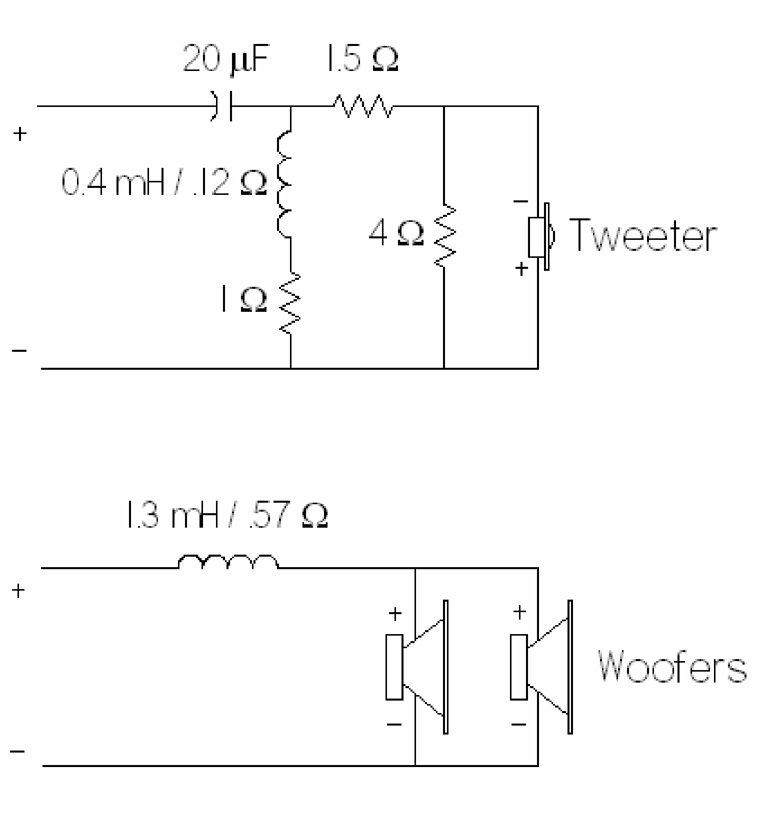
The plotted data in Figures 2 and 3, along with the phases which are not shown, were exported as "frd" and "zma" files and then read into a separate MathCad crossover simulation worksheet to design the passive circuits. I started the crossover design using a classic third order crossover with the low pass set at 1.6 kHz and the high pass set at 2.4 kHz. To get the best performance I used a resonance trap and an L-Pad on the tweeter and a Zobel on the woofer along with an independent baffle step circuit. This third order textbook style crossover required 15 parts per channel, 30 parts total. The SPL response is shown below in Figure 4. However, the cost and complexity of this crossover circuit sent me looking for other options.

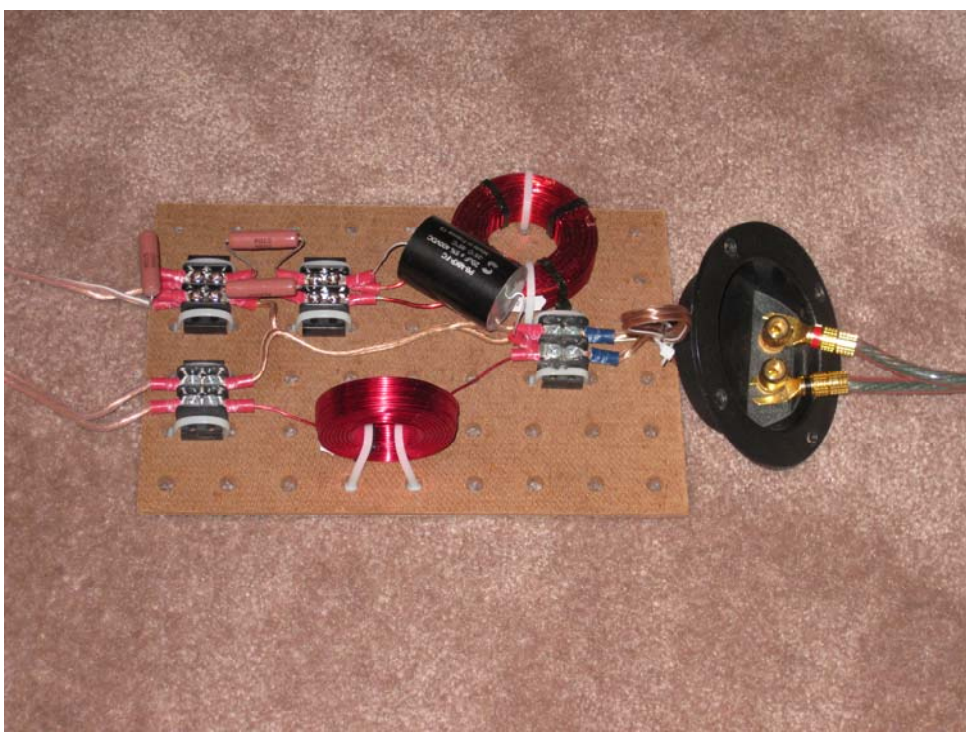
Figure 4 : System Anechoic SPL Response Using a 3rd Order Crossover



I searched the Internet for crossover designs and reverse engineered a number I found where measurements were presented. In particular I looked very closely at crossover designs where baffle step correction was included in the crossover components eliminating the need for a separate BSC circuit. The result of this effort was the crossover shown in Figure 5. The part count was reduced to 6 parts per channel, 12 parts total. Three of the parts per channel were low cost Mills resistors. The inductors were ERSE perfect lay air core coils while the capacitor was from Solen. All of the crossover parts, port tubes, and binding posts were purchased from Parts Express.

Figure 5 : Final Crossover Design and Assembly





The crossover was assembled on peg board external to the bass reflex enclosure. Two sets of leads, one for the paralleled woofers and one for the tweeter, were connected to the dual binding post on the back of the cabinet. The calculated electrical impedance is shown in Figure 6 and the simulated anechoic system SPL response is shown in Figure 7.

Figure 6 : Speaker System Electrical Impedance

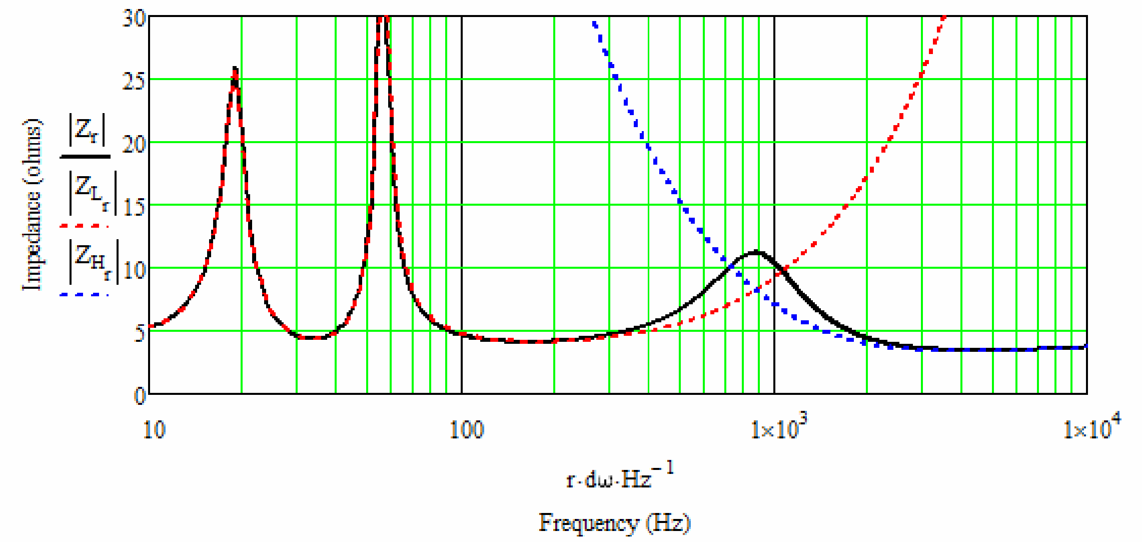
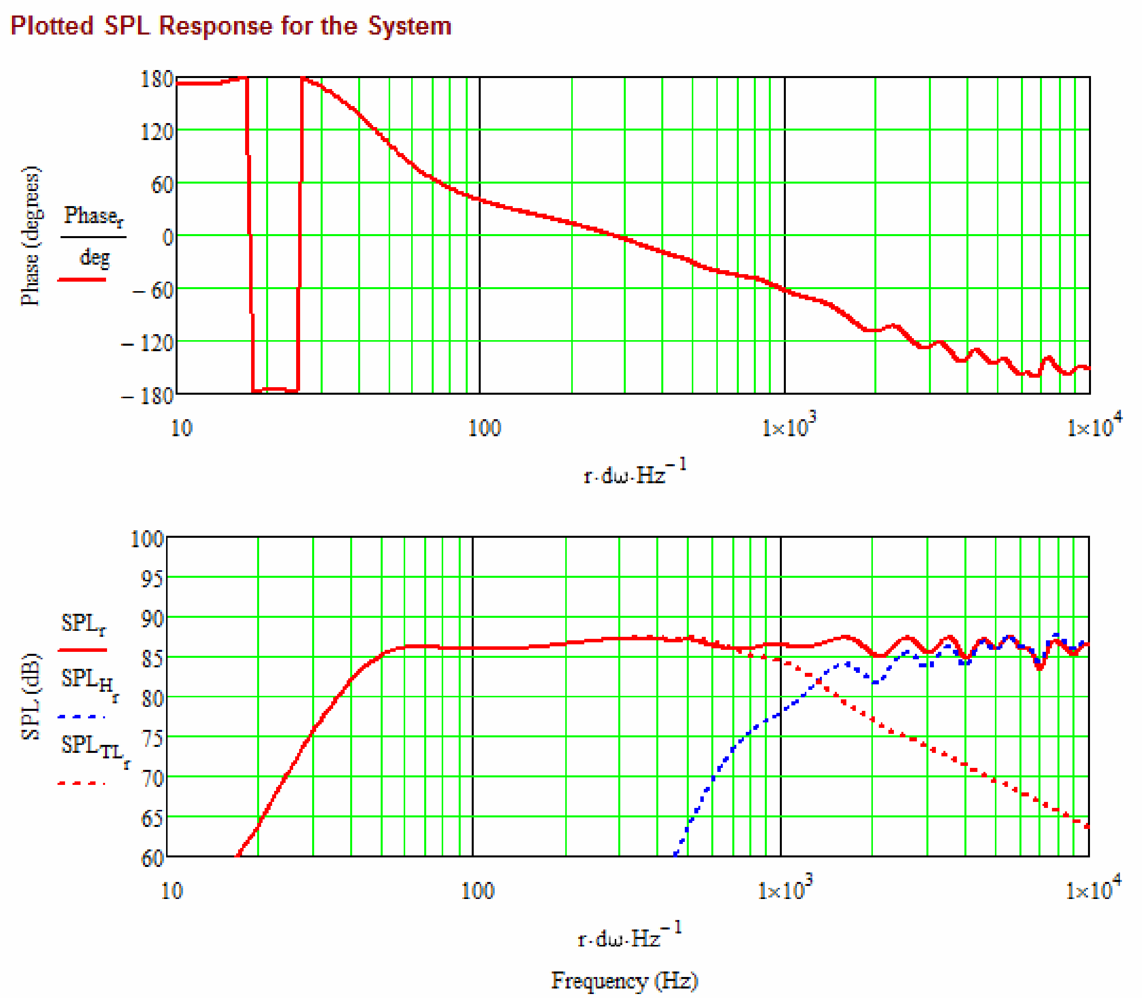


Figure 7 : System Anechoic SPL Response Using a 1st and 2nd Order Crossover



The calculated vertical SPL radiation pattern is shown in Figure 8 at 1300 Hz where the woofer and tweeter SPL curves cross in Figure 7. In Figure 8, the solid and dashed red traces are the woofers and port respectively. The blue trace is the tweeter. The black curve is the combined system SPL response at 1 m as a function of angular position vertically around the speaker. The dashed black line is a reference level of 86 dB. The calculated horizontal SPL radiation pattern is shown in Figure 9 with the same trace assignments.

Figure 8 : Vertical SPL Radiation Pattern at 1300 Hz

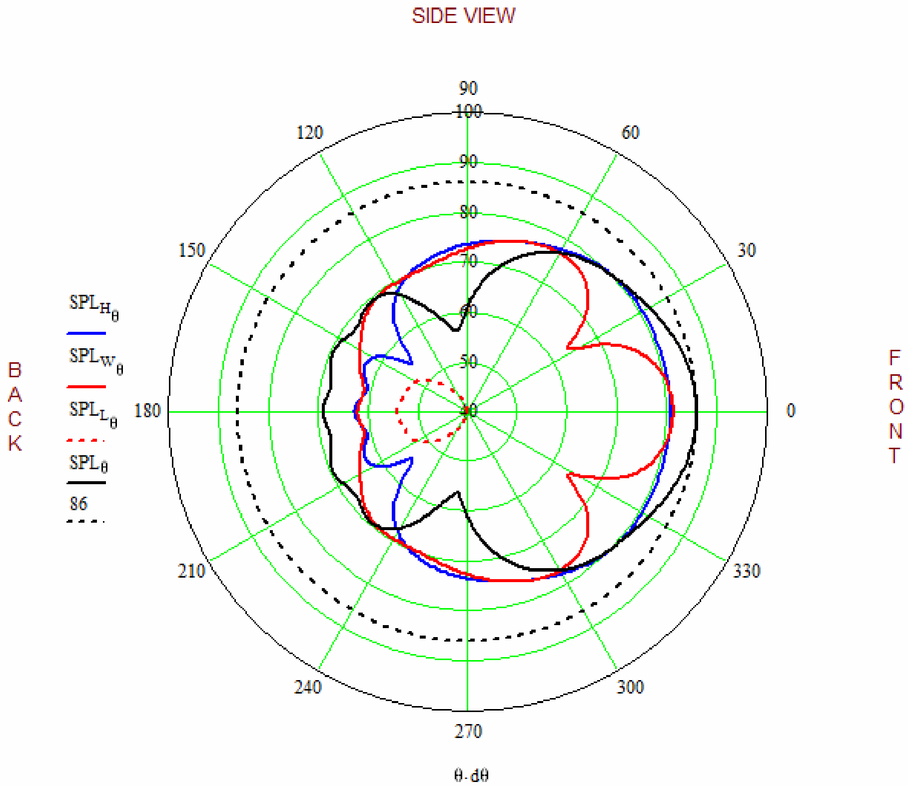
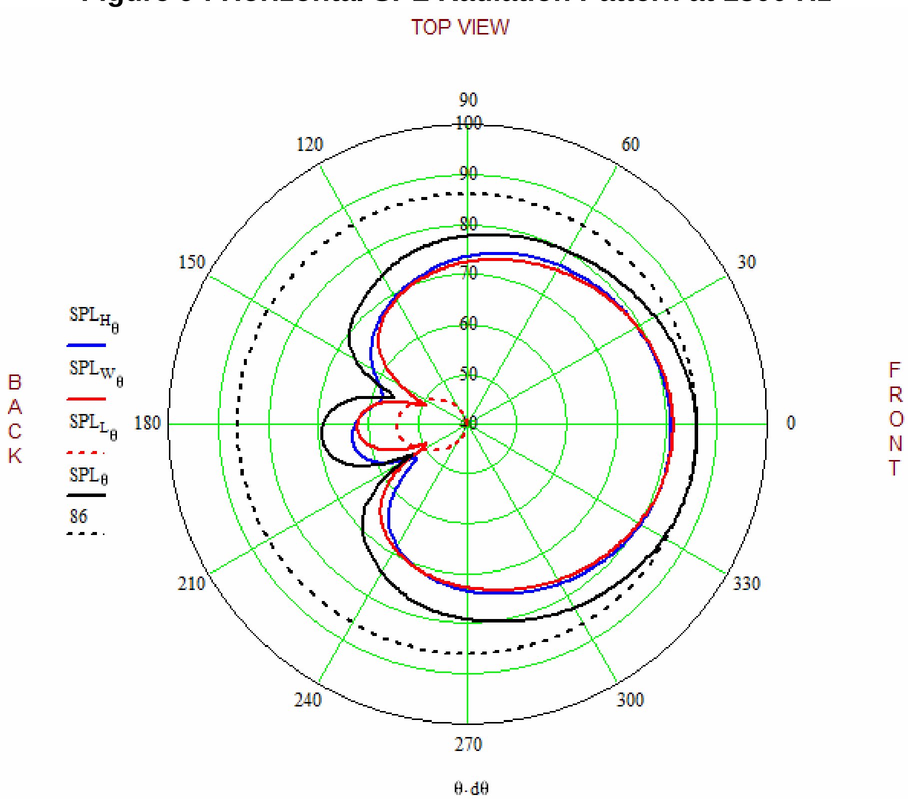


Figure 9 : Horizontal SPL Radiation Pattern at 1300 Hz



Measurements and Correlation with the MathCad Model :

The calculations were completed and the predictions looked really good so I built the enclosure using left over plywood from a variety of projects completed over the past 10 years. Listening to the finished speakers was high on my priority list and I did for several weeks before making in room SPL measurements with OmniMic and electrical impedance measurements with Praxis. For each measurement either an “frd” or “zma” file was saved and pulled into MathCad to plot against the model’s predictions.

The first measurements I made were the system electrical impedance and the near field SPL for one of the woofers and the port. Correlating these measurements against calculated curves indicates how accurate the low frequency response has been predicted. Figure 10, 11, and 12 show the correlation for the electrical impedance, woofer near field SPL, and port near field SPL respectively. In all plots the dashed curve is the measured result while the solid curve is the calculated prediction.

Figure 10 : System Electrical Impedance Correlation

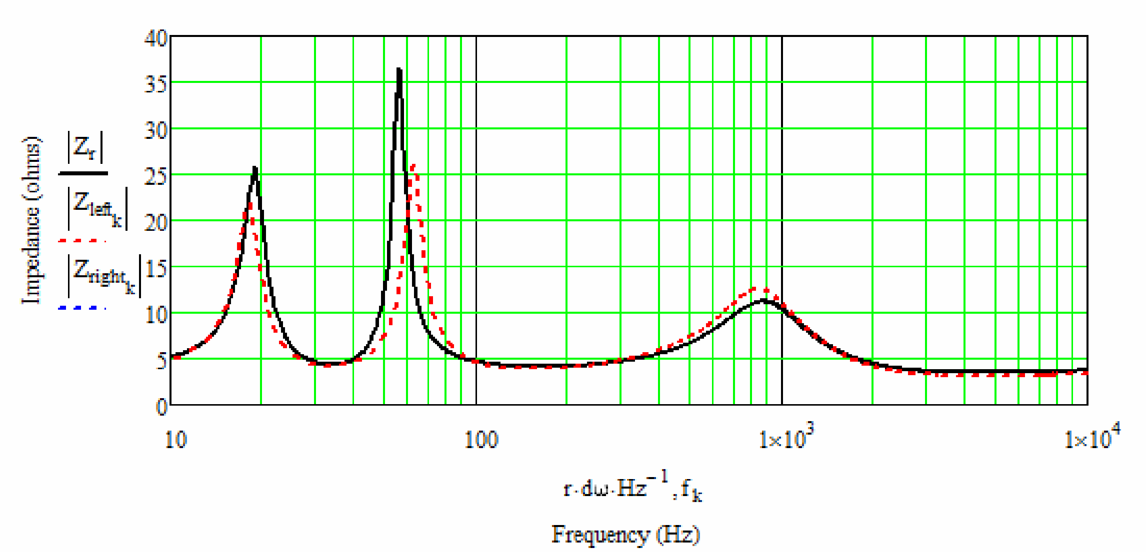


Figure 11 : Woofer Near Field SPL Correlation

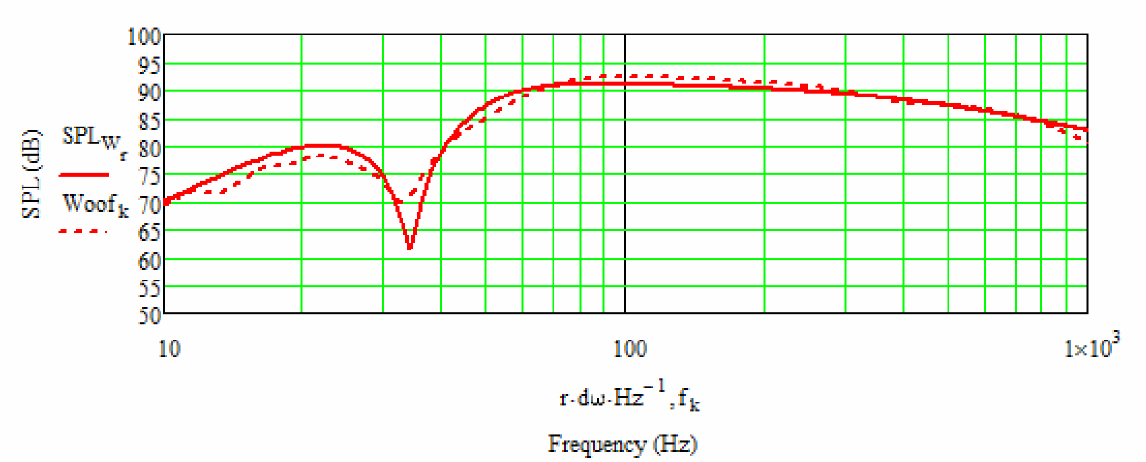
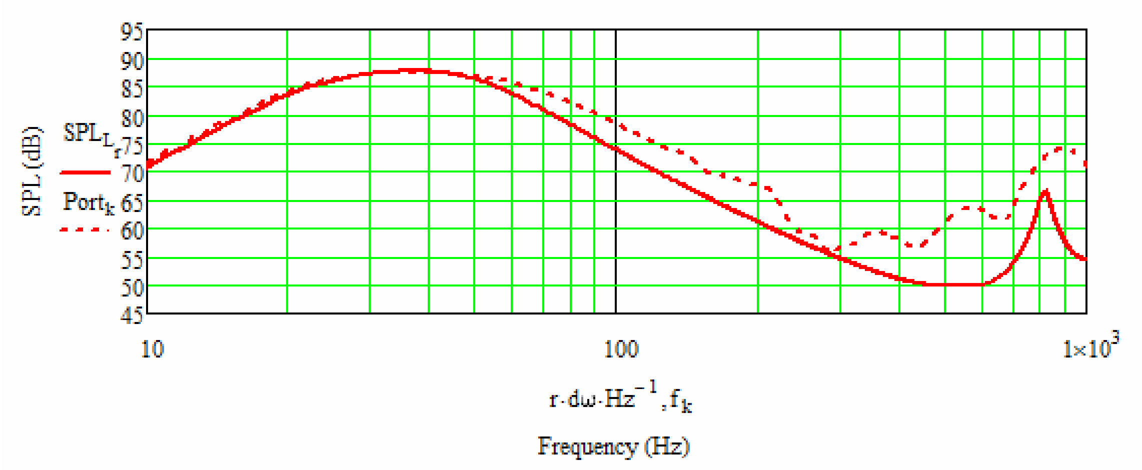


Figure 12 : Port Near Field SPL Correlation



The correlations looked good which indicates that the bass reflex enclosure was performing as predicted and the crossover was producing the expected impedance peak at ~850 Hz. In the port SPL plot a calculated peak can be seen at 800 Hz while measured peaks can be seen at approximately 350 Hz, 550 Hz, and 900 Hz. These three frequencies correspond to 7.5 inch, 12.3 inch, and 19.3 inch half wavelength standing waves respectively, very close to the internal dimensions of the enclosure. I currently have a 3D version of the MathCad worksheets almost complete, it will be interesting to see if these three peaks are predicted accurately.

Figure 13 plots the SPL of the woofer at 1 m with 1/12 octave smoothing applied. The solid red line is the calculated response, including the corner boundary, and the dashed red plot is the measured response. The corner reflections were responsible for the depression between 50 Hz and 200 Hz. The response above 2 kHz was not predicted accurately but looking back at the manufacturer's data sheet a rising on axis response can be observed beginning at 2 kHz which is not accurately modeled in the T/S parameter based MathCad worksheet

Figure 13 : Woofer with Low Pass Crossover SPL Correlation

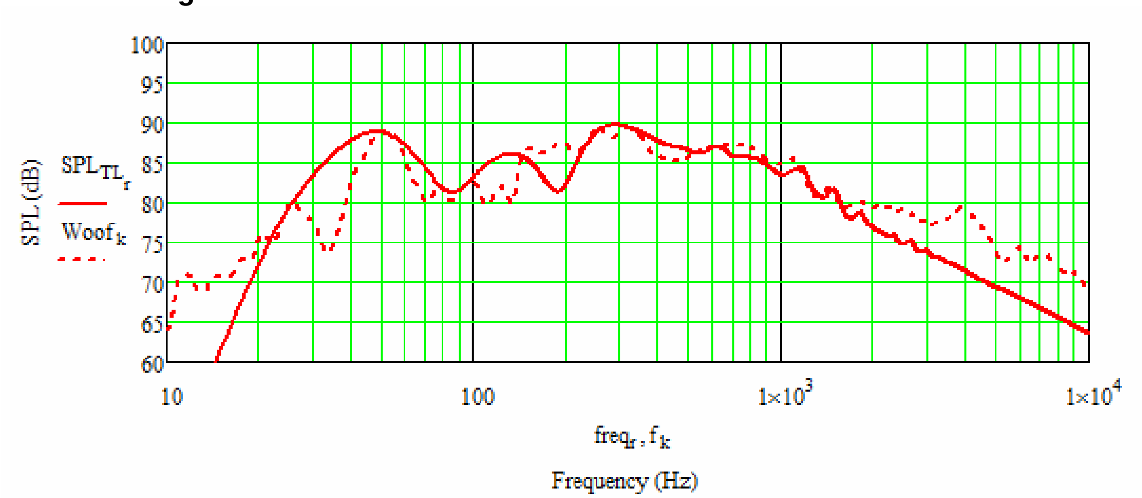


Figure 14 contains the solid blue calculated and dashed blue measured response of the tweeter and crossover again with 1/12 octave smoothing. The calculated response was much more ragged probably because of the 6 millisecond windowing applied to the measurements but not applied to the calculations. Overall the correlation is pretty good.

Figure 14 : Tweeter with High Pass Crossover SPL Correlation

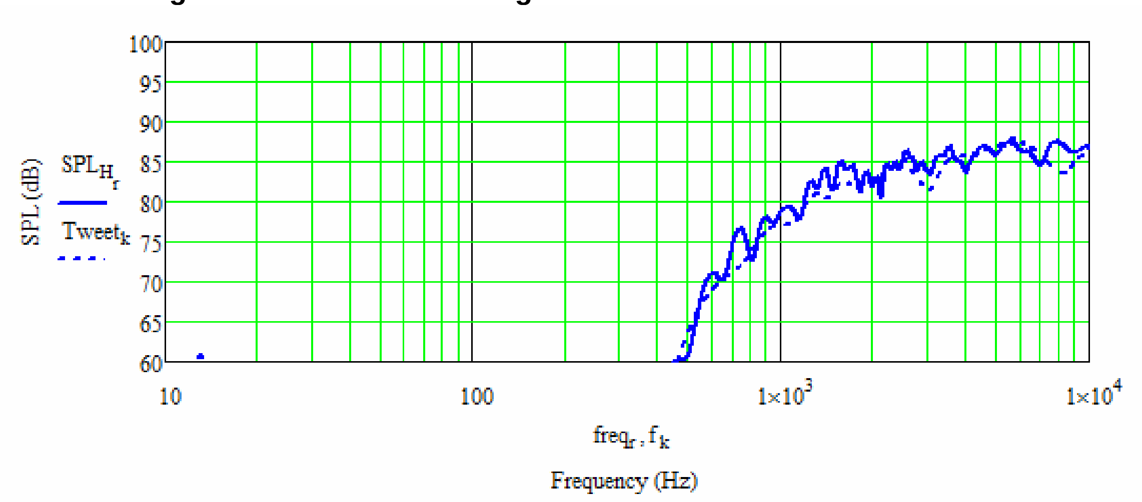


Figure 15 presents the final SPL prediction and measurement of the system at 1 m with 1/12 octave smoothing applied. The solid red line is the predicted response and the dashed red line is the measured response. The polarity of the input was flipped with respect to Figure 7 to produce a smooth monotonic plotted phase in the crossover region. Again the correlation looks very good.

Figure 15 : System SPL Correlation

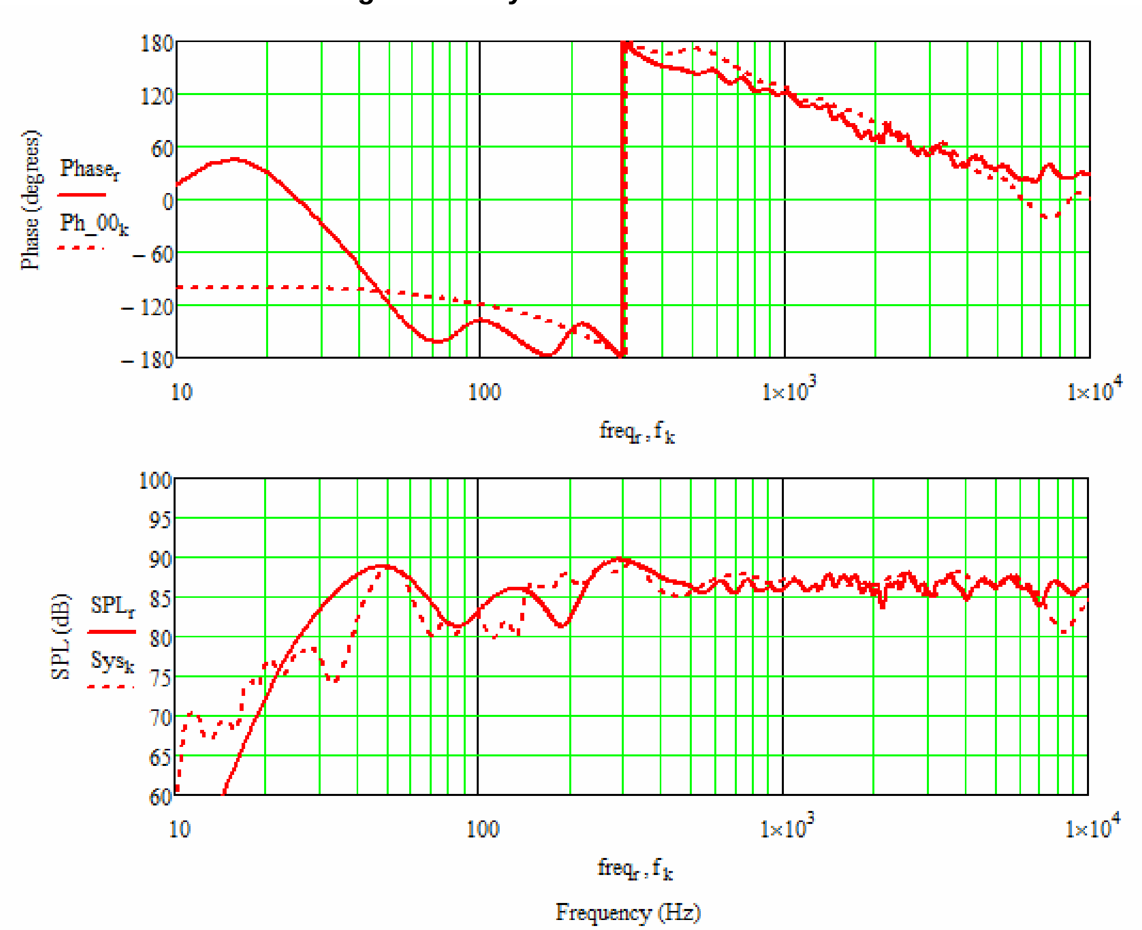
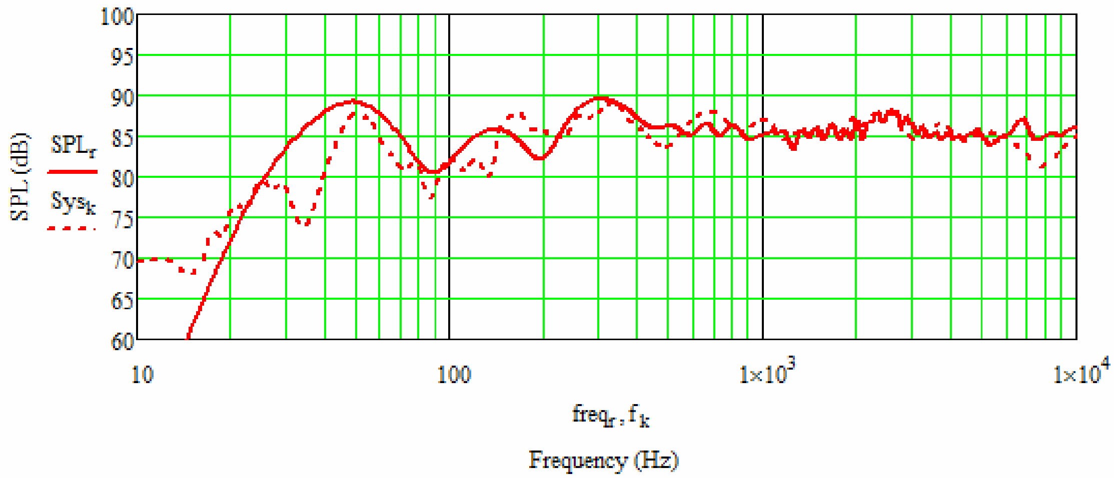
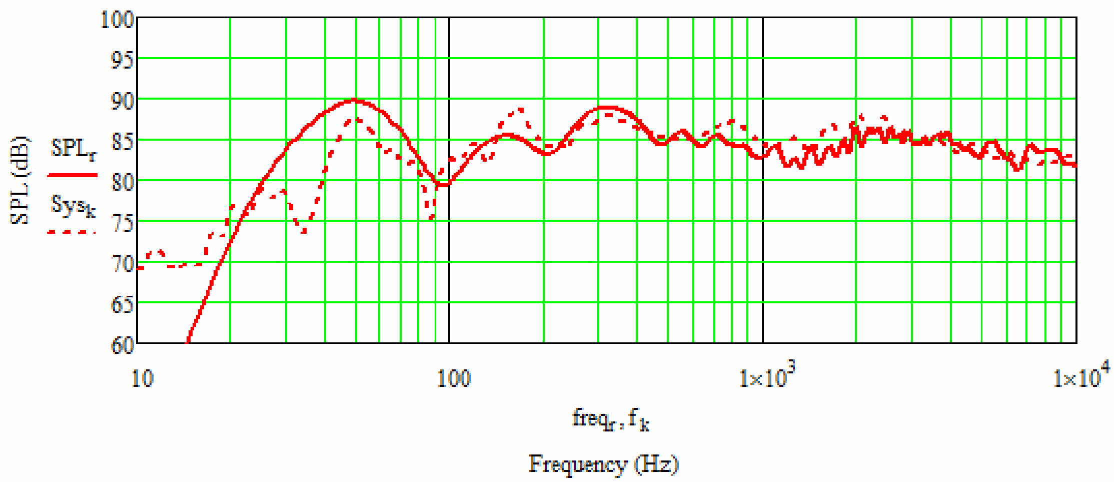


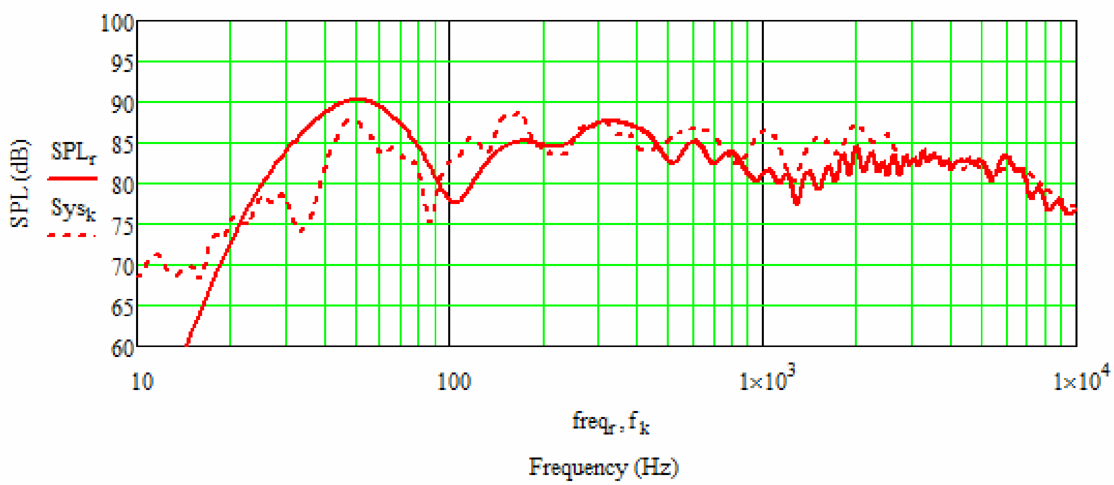
Figure 16 shows the off axis predicted and measured SPL system responses at 1 m with 1/12 octave smoothing applied. Again the solid curves were calculated and the dashed curves were measured. Figure 9 hinted at a smooth off axis response and this was proven out in the three different off axis graphs.

It should be noted that the SPL dip between 50 and 200 Hz was produced by the nearby room boundaries and the reflections that occur. The dip in these plots was unique to the 1 m measurement distance. At a longer measurement distance, or at the slightly off axis listening position, the broad dip would not exist and some other peak or null would be produced in the system SPL response plot. The room has a tremendous impact on a speakers SPL response and is often overlooked in the design process.

Figure 16 : System SPL Correlation at 15 degrees, 30 degrees and 45 degrees







System Voicing Options :

The anechoic response calculated and shown in Figure 7 represents a flat on axis design. Including the nearby room boundaries added a depression in the smooth response between 50 and 200 Hz as seen in Figure 15. The correlation achieved in Figure 15 supports the conclusion that the anechoic response was calculated accurately.

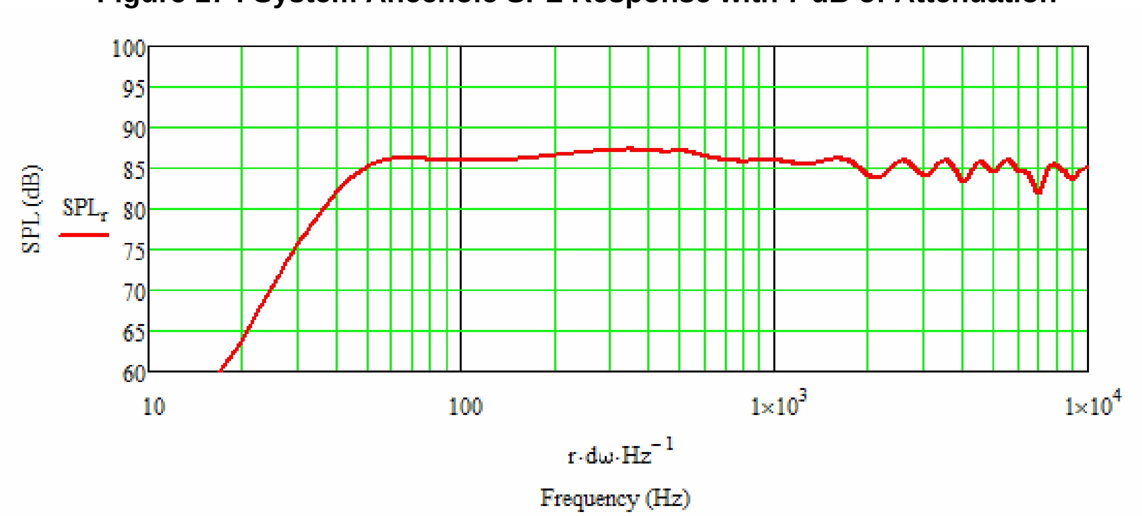
The general shape of the SPL response curve can be used to voice the speaker system. Some people prefer a flat on axis response while many other people like a gentle downward sloping SPL response at higher frequencies. The L-Pad portion of the high pass filter can be used to voice the system by providing a shallow slope to the SPL response above 1 kHz. The 4 ohm resistor, shown in parallel with the tweeter in Figure 5, can be replaced to influence the shape of the SPL response.

Table 1 presents a few different options while Figure 17 contains the plotted response for the -7dB case. The impact of tweaking the L-Pad values produces a subtle slope in the SPL response compared to the flat response presented n Figure 7.

Table 1 : System Voicing Using the L-Pad

Attenuation	R_series	R_parallel	SPL(1 kHz)	SPL(10kHz)	Delta SPL
-5	1.5	4.0	86.4	86.4	flat
-6	1.5	3.0	86.1	85.6	0.5
-7	1.5	2.5	86.0	84.9	1.1
-8	1.5	2.0	85.8	84.1	1.7
[dB]	[ohms]	[ohms]	[dB]	[dB]	[dB]

Figure 17 : System Anechoic SPL Response with 7 dB of Attenuation



Conclusions :

This was a two part project with two separate goals. First, the MathCad worksheets needed to be updated and the accuracy of the predictions tested. Second, a speaker was built and the performance measured and subjectively assessed after a few months of listening.

Starting with the MathCad upgrade, the initial design work using the worksheets held up and correlated well against electrical impedance and in room SPL measurements. There are a few more areas where I believe the accuracy of the calculations can be improved or extended but overall I am extremely happy with the results. I believe I can design a multi-way speaker and crossover on the computer using MathCad with some degree of confidence in the resulting performance.

As for the speaker build, everything that could go wrong did. This is probably the ugliest speaker enclosure I have ever built complete with inaccurate cuts and mistakes made that required significant rework. The finish seen up close is horrible. But since this is a proof of concept build with plans already formulating for a bigger and better design with a more exotic cabinet I probably will not need to look at this effort for an extended period.

The performance of the drivers and the crossover was not at all disappointing. I really like the sound of the Satori drivers and the crossover sounds seamless to my ears. These drivers deserve better and I am looking forward to working with them again in a more exotic enclosure design. The bass output from the oversized stand mounted bass reflex enclosure is more than adequate when called on to produce bass notes reaching down into the 40 Hz range. The system is not at all fatiguing and enjoyable to listen to continuously for many hours.

To be continued ……..