The Two-Year Transmission Line Speaker Design

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By Martin J. King, 9/23/23

Introduction :

I did not really work for two years designing and building this speaker as the title would indicate. But the elapsed time from first thinking about a new classic transmission line design, selecting and measuring drivers, trading off the physical enclosure options, building my final concept, to testing and listening did take a little over two years. I know I work slow, and two years does seem ridiculous, but there were a lot of tangents and other software development work that took place in this time span further sharpening my understanding of transmission line enclosures while adding more capabilities to my personal MathCad worksheets. This document is intended to provide more insights into this out of the mainstream enclosure type, potential trade-offs, and the methods used to complete a design so that measurements are only used for performance verification and final small tweaks to address driver and enclosure behaviors not easily or accurately simulated.

Initial Discussion :

Bass reflex and transmission line enclosures are both 4^{th} order speaker systems. For both speaker types, the enclosure produces the low frequency output around the tuning frequency while attenuating the driver's cone motion. The combined driver and port/terminus output yields a 4^{th} order high pass SPL response that rolls off at 24 dB/octave below the tuning frequency.

Most of the time designing a floor standing bass reflex speaker enclosure relies on alignment tables to determine the box's internal volume and the port's diameter and length. From the system alignment a rectangular enclosure can be sketched resulting in a height, width, and depth to produce the required internal volume. For a bass reflex enclosure placement of the woofer and port are not that critical. Changing an external dimension in the sketch has an easily determined impact on the other two external dimensions. At this point most DIYers build the box, mount the woofer and tweeter, and then use measurements of the drivers' electrical impedances and individual SPL responses to design a crossover that pulls it all together. The crossover should address the baffle step and edge diffraction as well as the relative positions of the woofer and tweeter on the front baffle to hopefully producing a smooth on-axis, off axis, and polar SPL response.

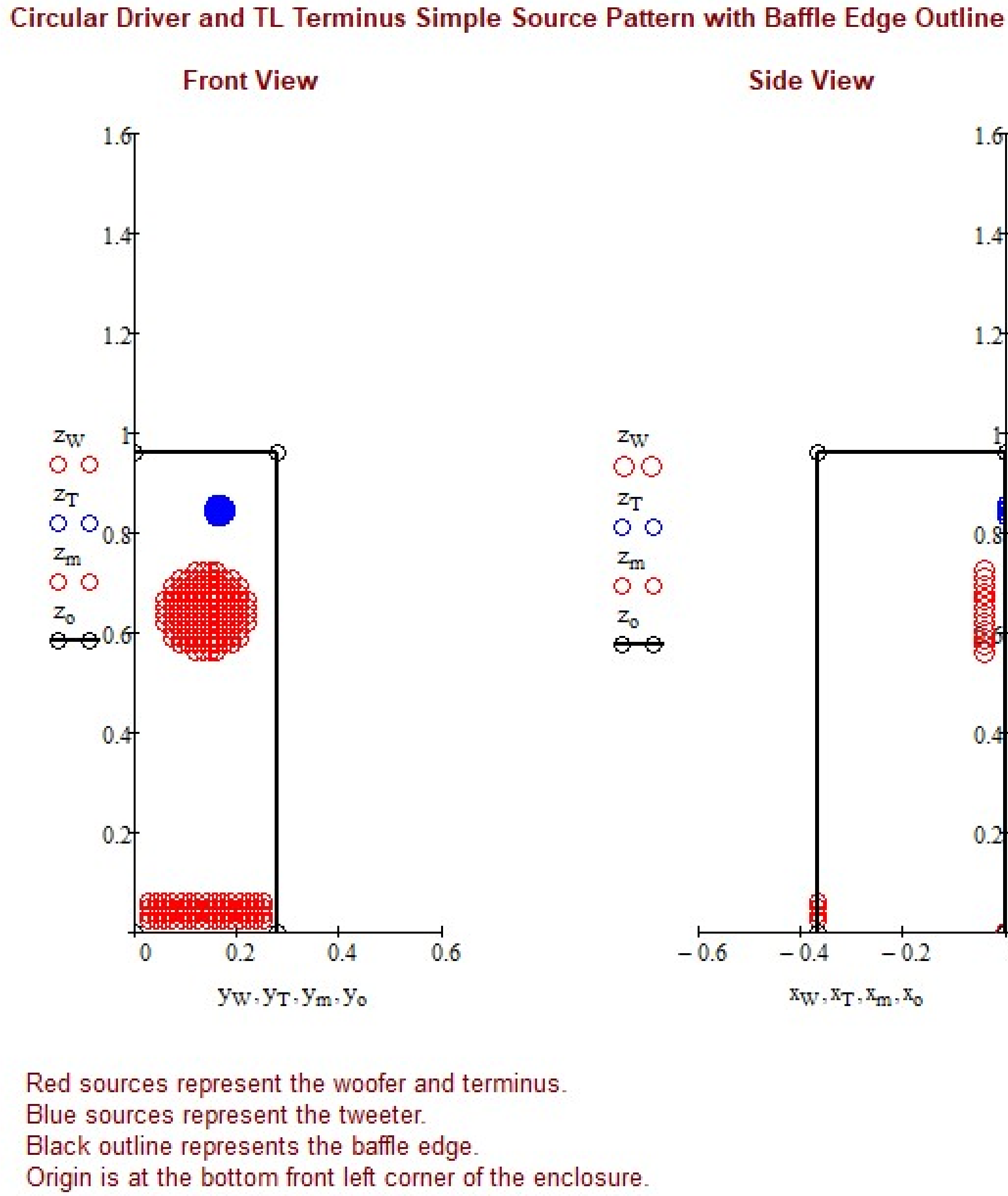
For the same floor standing enclosure, an equivalent transmission line is a more challenging sketching exercise. Internally it needs to have the same internal volume as the equivalent bass reflex enclosure. In addition, the transmission line's path needs to be folded, accounting for changing cross-sectional areas along the length, to yield an internal geometry that produces the correct tuning frequency. Also, the woofer is typically offset along the line's length to mitigate higher frequency standing waves. For the transmission line enclosure, changing an external dimension in the sketch creates havoc for the internal folding and the changes needed in the other two external dimensions. It is not always easy to produce a transmission line design that fits inside the equivalent bass reflex enclosure's rectangular envelope and still represents the simulation model. Designers of transmission lines tend to iterate between a sketch's geometry and the simulation's inputs to try and converge on a solution. Many times, this exercise is repeated for a variety of potential lengths and cross-sectional area profiles sucking up a lot of effort and time. One of the goals for this design exercise was to try and semi-automate this process of transitioning from simulation to physical geometry.

Before getting to the geometric modeling process, a few other key changes were made to the last available versions, from 2009, of the transmission line design worksheets. The MathCad models were upgraded to include a Thiele/Small (hence forth abbreviated as T/S) model for the tweeter, a complete set of compensation circuits (Zobel, trap, and L-Pad) for each driver, and either passive or active crossovers for each driver. Figure 1 shows an example of an upgraded MathCad model for a floor standing transmission line with a woofer, tweeter, and rear firing terminus. As in previous models the capability to add floor, side wall, rear wall, and ceiling reflections was retained. Not shown in Figure 1 are the many distributed edge sources around the perimeters of the front and rear baffles used to simulate the baffle step and baffle edge diffraction.

Adding the tweeter T/S model took advantage of redundancy in the complete set of T/S parameters. From an electrical impedance measurement of a tweeter, you can find R_e, f_s, Q_{es}, Q_{ms}, and L_{vc} (usually vary small). The cone area S_d can be calculated by measuring the tweeter diameter or by using the value from the manufacturer's datasheet. The remaining T/S parameters BL, V_{as}, and SPL/W/m are redundant, you only need one of these properties to calculate the other two. Using the SPL/W/m value taken from the manufacturer's datasheet, or from an actual acoustic SPL measurement of the tweeter, the values for BL and V_{as} can be back calculated and substituted into the new MathCad transmission line worksheets. A linear model of a tweeter's electrical impedance and SPL response can now be solved and plotted just like the woofer's solution and plots. Comparison with the manufacturer's measured electrical impedance and SPL response should confirm the accuracy of the tweeter's T/S model.

Missing from the simulation predictions are non-linear driver or enclosure behaviors and any cone break up resonances. When selecting drivers for use over an intended frequency range it is key to design away from these conditions for the simulation results to remain valid and be representative of what can be expected from the final speaker design/build. If done correctly measured results match the MathCad worksheet predictions reasonably well. Just like the woodworker's rule measure twice and cut once, now my goal is to simulate many times and only build once.

Figure 1 : MathCad Model of a Two-Way Transmission Line



Designing a Folded Transmission Line Enclosure :

One of the significant detours in this design effort was readdressing the original transmission line alignment tables first made available in 2006. The resulting new tables[(1)] are based on the bass reflex alignment tables found in the Loudspeaker Design Cookbook[(2)]. Repeating from above, bass reflex and transmission line enclosures are both 4th order systems with a 24 dB/octave roll-off below the tuning frequency. The key result from the new transmission line alignment tables is that equivalent bass reflex and classic transmission line enclosures have the same internal volumes and the same tuning frequencies. A classic transmission line is defined as having an area profile along the length that is monotonically tapering, straight, or expanding without any restrictions or expansions along the length or at the open end/terminus.

To design a bass reflex enclosure using the alignment tables in the Loudspeaker Design Cookbook[(2)], enter one of the tables and for a driver's Q_{ts} obtain values for the parameters H, α, and f_3/f_s. The value of α is used to calculate the volume of air in the enclosure V_b from the driver's V_{as} property. The value of H is used to calculate the enclosure tuning frequency f_b from the driver's resonant frequency f_s. Finally, the -3 dB point can be calculated relative to the driver's resonant frequency f_s using the ratio f_3/f_s. For the bass reflex enclosure, the internal volume (the stiffness) and the port dimensions (the mass) determine the enclosure's tuning frequency.

$$V_b = V_{as} / \alpha \text{ and } f_b = H \times f_s$$

To size the equivalent classic transmission line enclosure, the same alignment table procedure is followed to determine the enclosure's volume V_b using α and the tuning frequency f_b using H. A transmission line's length L is calculated consistent with the tuning frequency f_b and the line's cross-section area taper ratio, TR = S_L / S_0. Unlike the ported enclosure, the geometry of the transmission line's folded path (distributed mass and stiffness) determines the tuning frequency.

$$V_b = ½ \times (S_0 + S_L) \times L$$

Substituting $V_b = V_{as} / \alpha$ and $S_L = TR \times S_0$ into this equation you can solve for the cross-sectional areas at the closed end S_0 and the open end S_L.

$$S_0 = (V_{as} / \alpha) \times \{1 / [1/2 \times (1 + TR) \times L]\} \text{ and } S_L = TR \times S_0$$

These calculated geometric properties S_0, S_L, and L produce the correct equivalent transmission line enclosure volume and tuning frequency. The alignment tables article showed that for every TR = S_L / S_0 a different length L is required to maintain the same tuning frequency and low frequency response. The main difference between transmission line designs, with different TR's, is that the frequencies of the harmonics are shifted higher for lower TR's and lower for higher TR's compared to a straight constant cross sectional area TL (TR = 1.0) which has predictable harmonic frequencies.

The definition of L can lead to some confusion. The calculated length $L_{calculated}$ is really the effective length of the TL path, it is the sum of the physical length plus an added correction length representing the open-end acoustic impedance boundary condition.

$$L_{calculated} = L_{effective} = L_{physical} + L_{end\ correction}$$

If the alignment calculated length is used as the physical length of the TL, the fundamental tuning will be a little lower than expected. For a tapered TL, this slight mismatch in the definition of length will have a very small impact on the simulated results. My recommendation is to not worry about it, use the value of $L_{calculated}$ as the physical length, and proceed to simulate and tweak the TL design to achieve an optimized design.

In general, if a bass reflex enclosure design exists a family of equivalent transmission line enclosures can be derived with the same tuning frequencies and internal volumes. From a straight transmission line to a highly tapered transmission line a continuum of geometries will have essentially the same low frequency SPL response. This continuum of transmission line geometries was used to produce several families of folding geometries that fit into a rectangular enclosure with an offset woofer. Down selecting to a final design was done trading off other geometric features of the speaker and the calculated system SPL response as described in the following sections.

Folded Geometry :

For a given TL alignment, folding it into a rectangular box and positioning the woofer becomes the challenge. You can find many creative examples of folded TLs on the Internet; I focused on single folds to produce a tower style rectangular enclosure. Templates were set up in MathCad that iterated a minimum number of input dimensions (enclosure height, width, depth, material thickness, divider length and angle, and woofer offset) to produce folded geometries consistent with the TL's alignment parameters S_0, S_L, and L. The detailed MathCad sections inputs were automatically populated from the folded geometry. Different templates were created, four examples are shown in Figure 2 through 5 along with the resulting MathCad sections model. Like all other TL/horn simulation programs, the MathCad sections modeling was done assuming a straight unfolded model with local bulges in cross-sectional areas to represent the 90-degree or 180-degree bends.

From the templates and the TL alignment, buildable geometries were derived producing a final enclosure representation, as shown in Figure 1 for example. The external enclosure dimensions, placement of the woofer and tweeter, fiber stuffing density and location, position of the terminus, and the crossover type and properties were all defined in a single pass MathCad worksheet. The calculated outputs included SPL response on and off axis, electrical impedance, woofer cone displacement, terminus air velocity, and polar response factoring in the baffle geometry. The woofer/terminus/tweeter layout were automatically updated and replotted any time one of the geometric input variables was adjusted/tweaked.

Reviewing Figures 2 through 5, and carefully looking at the MathCad sections plot, the internal enclosure properties are for the same driver and the same TL alignment just the folding scheme is different. When the SPL responses were calculated for each geometry, the trends in the plots were the same but the magnitudes of small peaks and dips shifted in frequency due to the relative locations of the driver and terminus. Adding in a floor and wall reflections further accentuated the differences in the final SPL response for each geometry. Most TL freeware programs calculate the SPL response as if the driver and terminus are coincident (although Hornresp does allow a distance between the woofer and terminus) and mounted in an infinite baffle. To really get a more accurate result the geometry of the enclosure, the layout of the front and rear baffle, and the locations of the woofer and terminus are required.

This template style of MathCad worksheet is what I will use in future TL and back loaded horn designs to link simulation models to real world enclosure dimensions in one pass. Running a scoping simulation is great but not much use if a buildable enclosure is not physically possible.

Figure 2 : Single Fold Tapered TL Geometry with Bottom Rear Terminus and the MathCad Sections Input

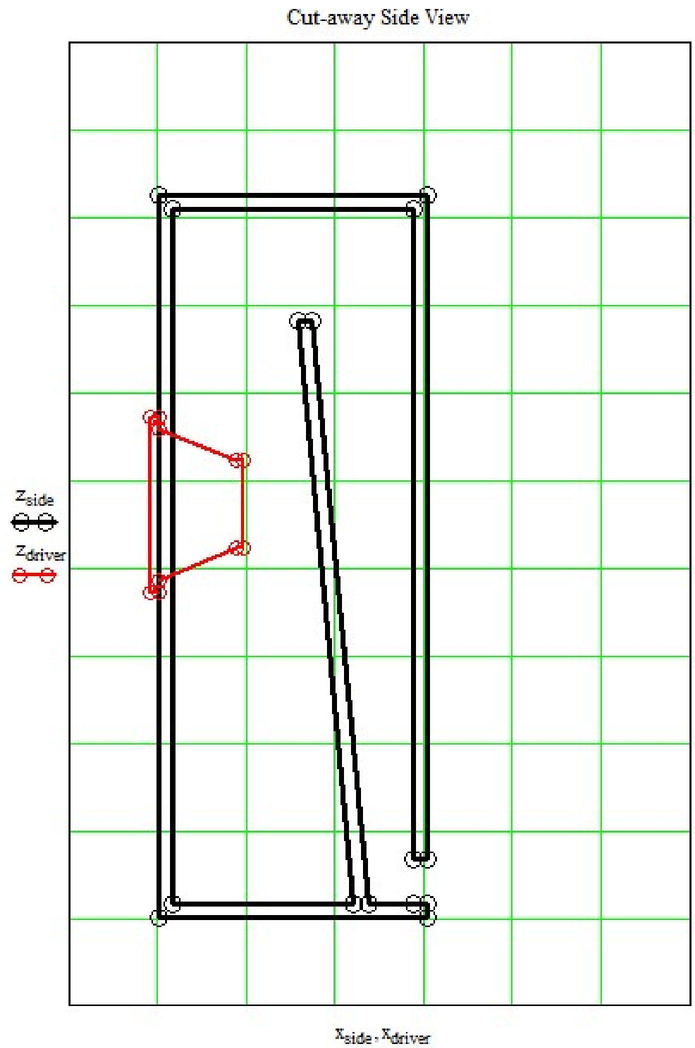


Figure 3 : Single Fold Tapered TL Geometry with Top Rear Terminus and the MathCad Sections Input

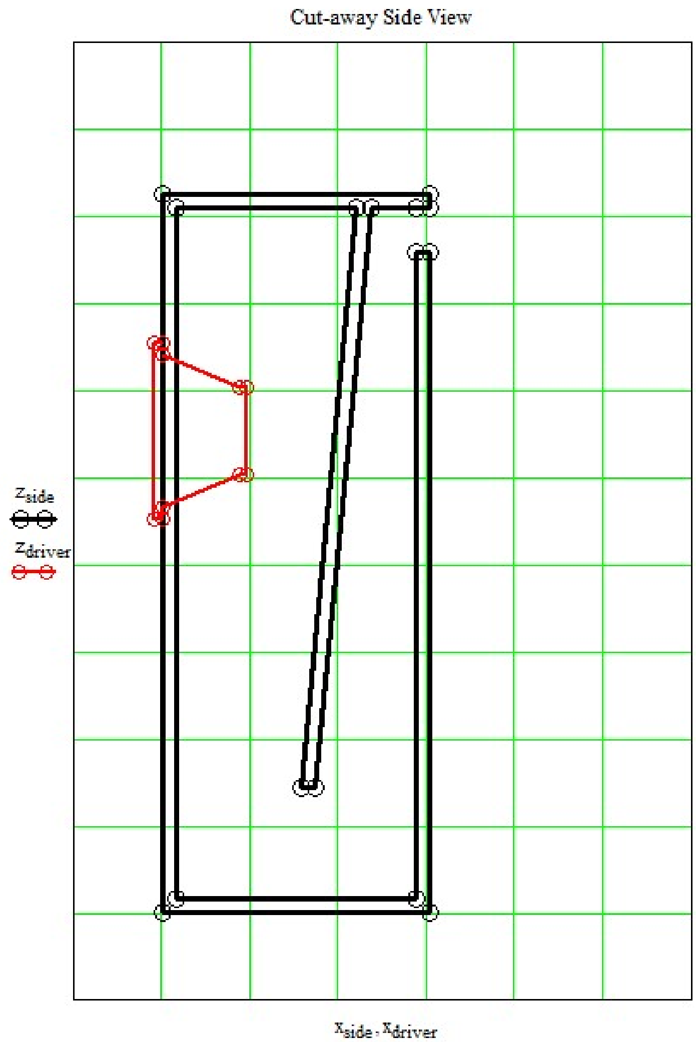


Figure 4 : Comma Folded Tapered TL Geometry with Bottom Front Terminus and the MathCad Sections Input

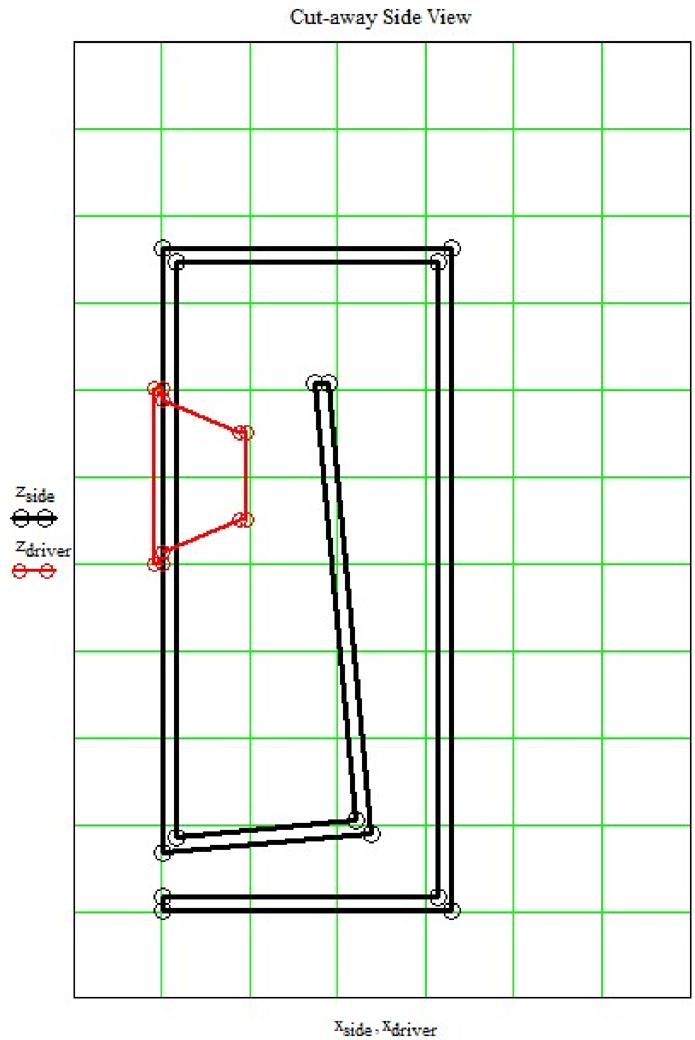
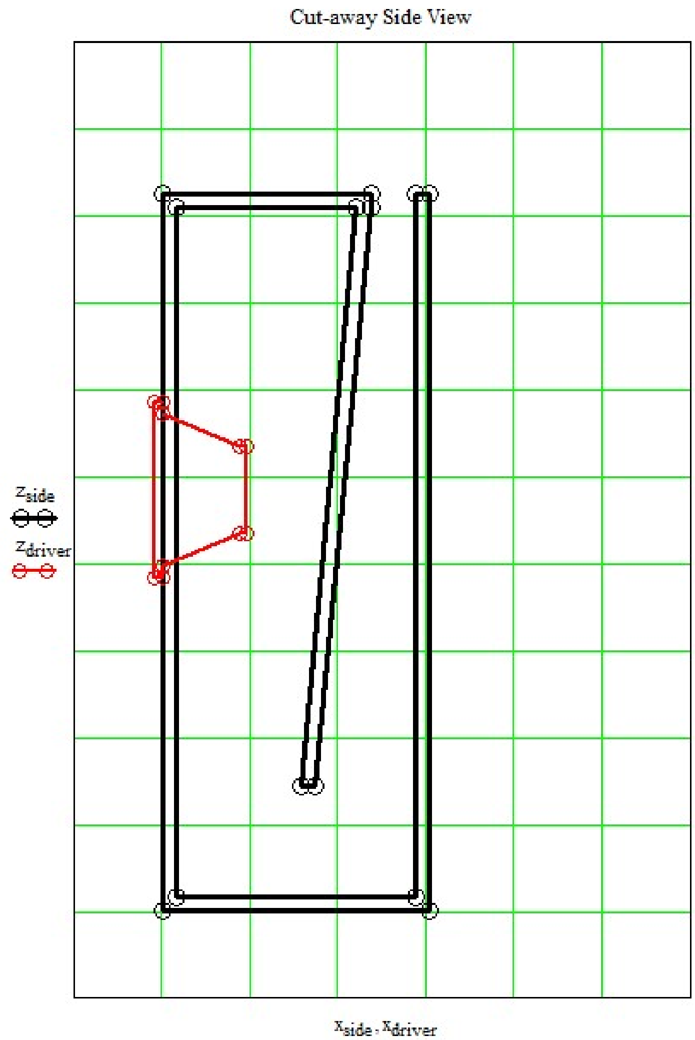


Figure 5 : Single Fold Tapered TL Geometry with Top Terminus and the MathCad Sections Input



Driver Selection and Measured T/S Parameters :

I decided to reuse the SB Acoustics Satori TW29R tweeters from a previous speaker build. For a mid-woofer I looked at and simulated a few well regarded makes and models in various TL configurations. In the end I decided to stick with the Satori line of drivers and selected the WO24P-4. Figure 6 presents the manufacturer's T/S parameters (Spec column) along with the individual driver measured values (1 and 2 columns), the average measured values (green column), and a calculated consistent set of values (red column) used as inputs to the MathCad design simulations.

Figure 6 : Derived T/S Parameters Using Measurements and Data Sheets as Inputs

		Satori TW29R T/S Summary				
Parameter	Spec	1	2	Average	Consistent	Units
fs	600	677	666	672	671.7	Hz
Qes	1.220	1.421	1.329	1.375	1.375	-
Qms	2.000	2.226	2.202	2.214	2.214	-
Qts	0.758	0.867	0.829	0.848	0.848	-
Re	3.00	3.1	3.0	3.05	3.05	ohm
Ls	20.00	17.22	16.27	16.75	0.017	uH
Rp		0.379	0.511	0.445	0.445	ohm
Lp		24.93	35.13	30.03	0.030	uH
Vas					0.022	liter
BL	2.000				1.758	N-A
Sd	9.60	9.60	9.60	9.60	9.60	cm^2
Mms	0.450				0.33	gm
Cms					0.17	m m/N
SPL	92.50				93.00	dB/W/m

		Satori WO24P-4 T/S Summary				
Parameter	Spec	1	2	Average	Consistent	Units
fs	28.000	32.088	33.529	32.809	32.81	Hz
Qes	0.420	0.536	0.554	0.545	0.545	-
Qms	6.700	7.259	8.015	7.637	7.637	-
Qts	0.400	0.499	0.518	0.509	0.509	-
Re	3.30	3.30	3.30	3.30	3.30	ohm
Ls	290.00	350.80	393.40	372.10	372.10	uH
Rp		0.77	0.71	0.740	0.740	ohm
Lp		579.20	610.40	594.80	594.80	uH
Vas	71.00	49.28	45.18	47.23	48.31	liter
BL	7.600	7.503	7.544	7.524	7.524	N-A
Sd	0.00	255.00	255.00	255.000	255.00	cm^2
Mms	42.000	45.390	45.350	45.370	45.353	gm
Cms	0.770	0.542	0.497	0.519	0.519	m m/N
SPL	87.09	86.65	86.70	86.68	86.80	dB/W/m

TL Enclosure Design Methods and Goals :

The alignment tables[1] were used to produce a range of tapered TL geometries. Tapered TL configurations were preferred since they push the harmonics of the tuning frequency higher in frequency. If the woofer was offset to mitigate the 3/4 wavelength mode then the frequency of the first excited harmonic, the 5/4 wavelength mode, would be pushed high enough in frequency so fiber damping effectively tamed any significant ripple. Selecting which taper ratio came down to other design goals as shown below.

Tapered TL Design Goals :

1. Single fold floor standing tower enclosure. Rectangular enclosure of reasonable dimensions (in other words not a refrigerator sized box).
2. Woofer offset along the TL length to mitigate the 3/4 wavelength mode.
3. Tweeter is located at a seated listener's ear height of approximately 33 inches.
4. Woofer/Tweeter spaced close enough to control the SPL vertical polar pattern near the crossover frequency.
5. Tweeter offset from the horizontal center of the baffle to minimize baffle diffraction ripple.
6. A crossover that produces a smooth SPL response and addresses the baffle step loss at low frequencies.
7. A final SPL response calculated on the axis of the Tweeter that monotonically slopes down with increasing frequency resulting in a 2 to 4 dB total reduction in high frequency output.
8. Complete engineered design to be determined before building so testing only used for final verification and tweaking.

As described earlier, the MathCad models were set up to simulate the enclosure size and source layout along with nearby room boundaries (floor, side and rear walls, and the ceiling). The SPL response was then calculated at any location in space as a function of frequency or at any frequency as a function of radius and polar position.

The more information entered for the calculations the more complicated the SPL results, for example nearby room reflections generated multiple peaks and dips in the SPL response. Each room boundary creates a mirror image of the speaker on the other side of the boundary producing reinforcement and cancellation in the SPL response as a function of frequency and distance. Every different room position produced a different SPL response, I was quickly drowning in data. To simplify the analysis, I decided to calculate the anechoic SPL response on the axis of the tweeter at a 3 meters distance. Most speaker measurement data is generated to simulate the anechoic response at 1 meter on the axis of the tweeter, I extended the 1 meter to 3 meters to allow the tweeter, woofer, and TL terminus to blend in a more representative way at an approximate listening position. At 1 meter the distance and angle to the listening position for each source is significantly different for a floor standing enclosure. This greater 3-meter distance de-emphasized the output from the tweeter which lies on the shortest most direct path.

Figure 7 contains potential TL geometries for various taper ratios derived from the SBB4/BB4 alignment tables[2]. Input cells are shaded blue and output cells are shaded green. The TL lengths and cross-sectional areas were tabulated resulting in a constant internal enclosure volume of approximately 70 liters.

Figure 7 : Potential Tapered TL Geometries

Tapered TL Alignment Options					
Driver :	Satori WO24P-4				
fs	32.81	Hz			
Qts'	0.58	Include Series Resistance			
Vas	48.31	liters			
Sd	255	cm^2			
SBB4/BB4 Alignment					
QL	15				
H	1		fb	32.81	Hz
alpha	0.6868		Vb	70.34	liter
f3/fs	0.8224		f3	26.98	Hz
SL/S0	SF	L (inches)	S0/Sd	SL/Sd	
1	1	103.19	1.05	1.05	
0.5	0.87	89.78	1.61	0.81	
0.333	0.8	82.56	1.97	0.66	
0.2	0.71	73.27	2.47	0.49	
0.1	0.62	63.98	3.09	0.31	

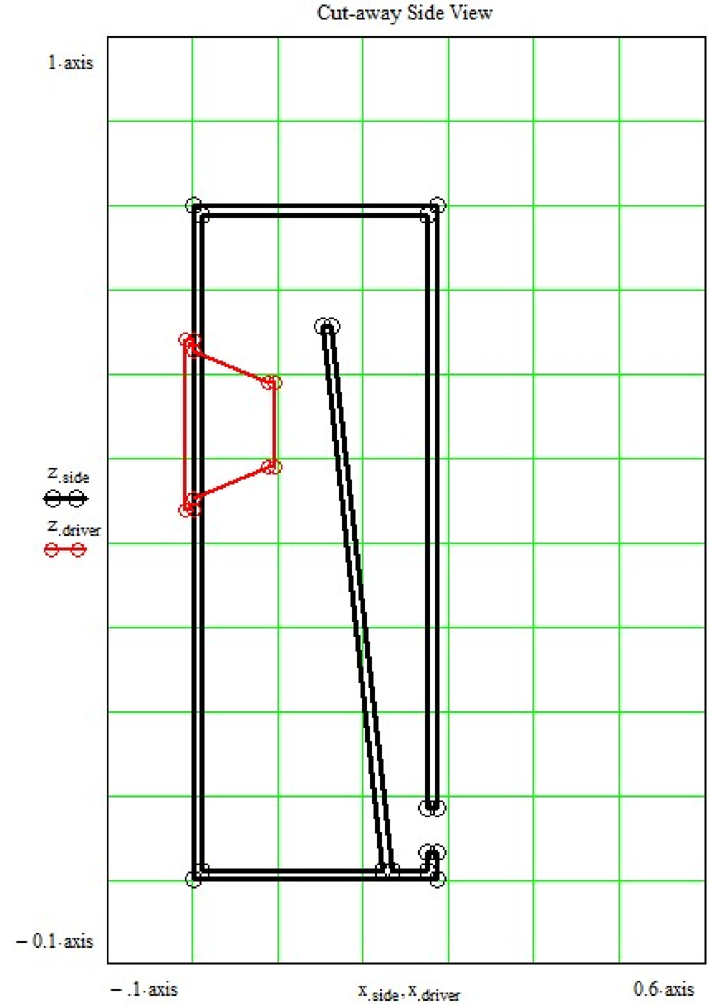
The tapered TL alignment options were run through the different MathCad templates to assess how many of the goals would be achieved. Trade-offs were studied and a TL geometry was selected, shown in the red box, that is consistent with the layout style in Figure 2.

Final Design, Simulation Checks, and Build :

Jumping right to the design, Attachment 1 contains dimensioned sketches of the final design. An important feature of the design are brass threaded rods used to clamp the sides to the center structure of the TL. I wanted a TL enclosure that would lend itself to experimentation so opening it back up to replace fiber stuffing with acoustic foam and the ability to tweak a passive crossover outside the enclosure then later relocate it inside the enclosure drove this concept. Details of the build steps can be seen in the pictures contained in Attachment 2 along with definition of the materials and parts used.

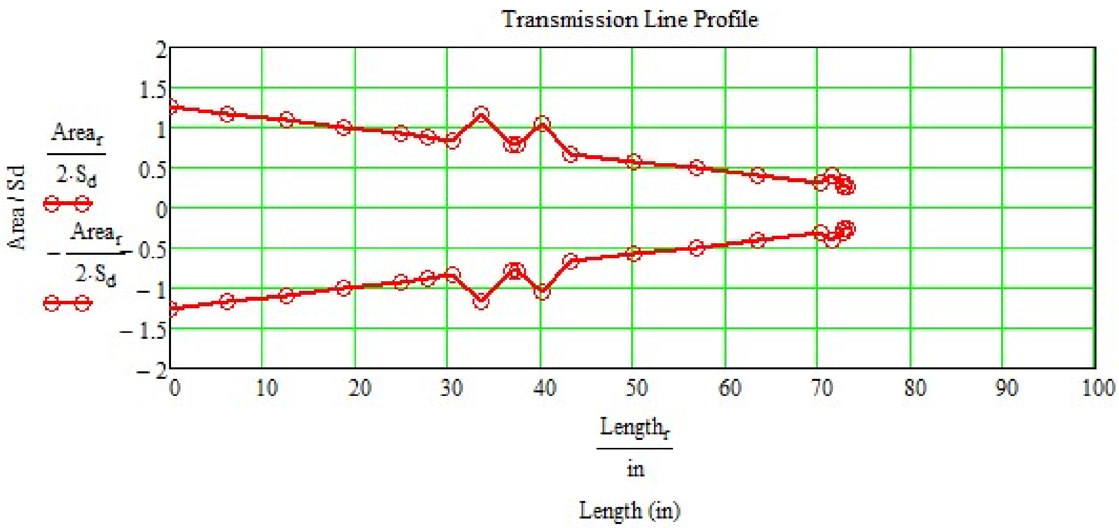
Figure 8 shows the MathCad model of the final enclosure, it is a modification of the layout in Figure 2. The design is a 5:1 tapered TL with a length of 73.2 inches and an internal volume of 75.4 liters (a little bigger than the target alignment shown in Figure 7).

Figure 8 : Final Single Fold Tapered TL Geometry with Bottom Rear Terminus and the MathCad Sections Input



Before building the enclosure, the design was double checked by calculating the resonant frequencies and modes shapes of the air column inside the TL with two MathCad 1D worksheets and independently with a 3D ANSYS(3) finite element model as shown in Figures 9 and 10 respectively. For the MathCad worksheets both traditional corner modeling and the advanced centerline corner modeling, an alternative corner geometry model, were simulated.

Figure 9 : Traditional and Advanced Centerline Corner Modeling Geometries



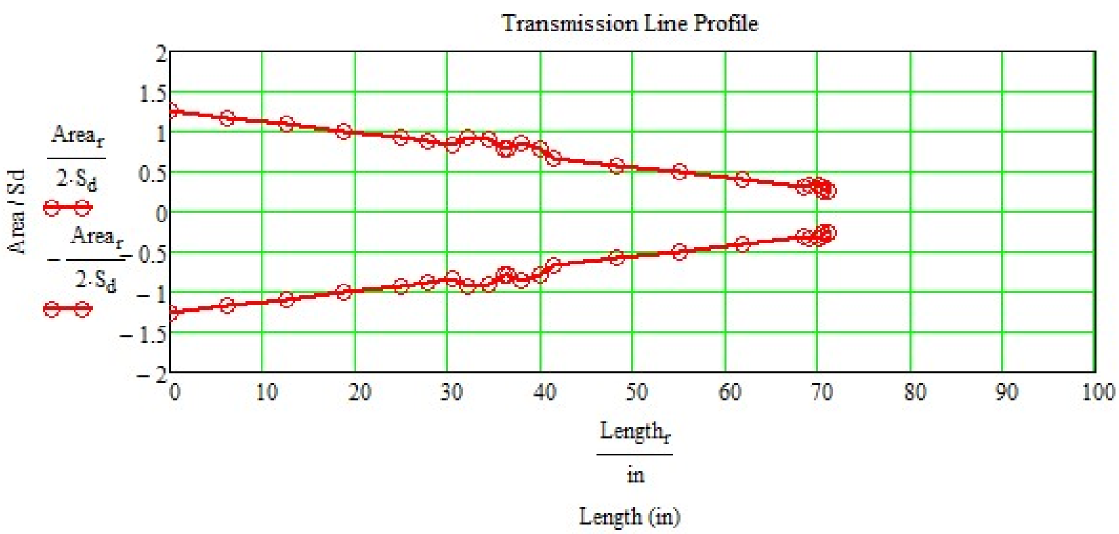
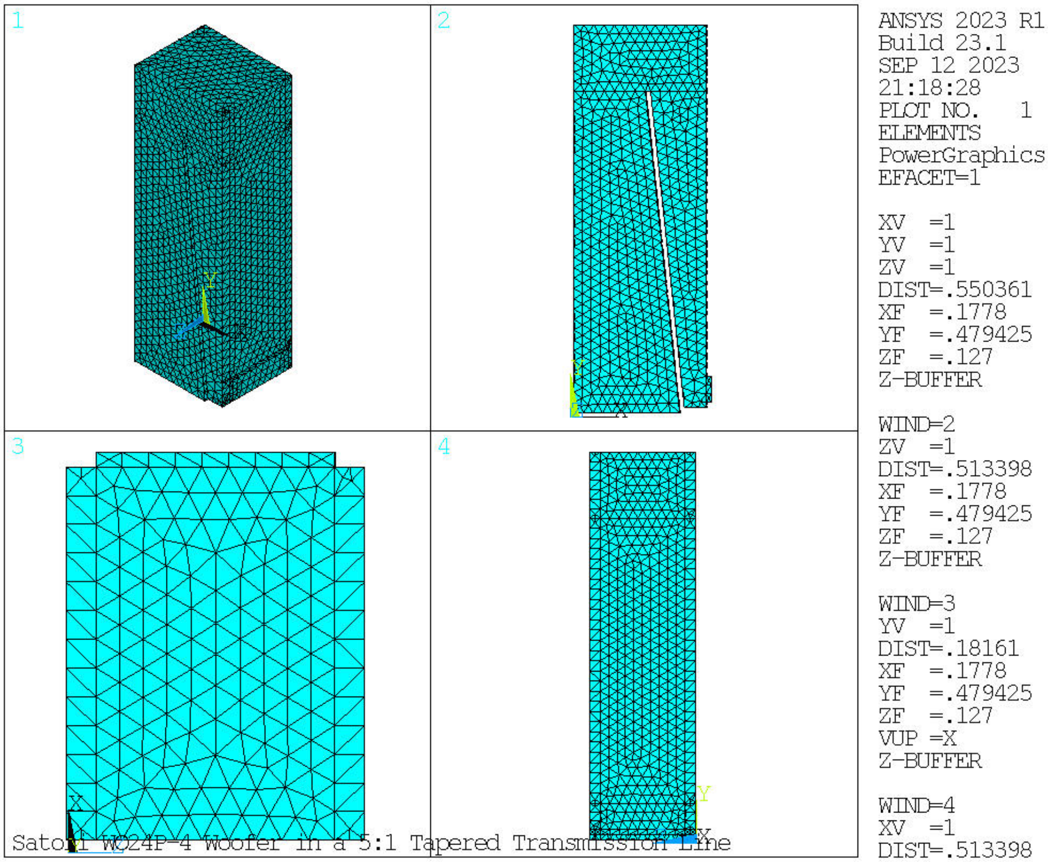


Figure 10 : ANSYS Finite Element Model



All three models assumed a perfect boundary condition at the open end, pressure is zero and the derivative of the velocity profile is zero. This removed any assumption for an acoustic impedance boundary condition at the open end of the TL resulting in an apples-to-apples comparison of the results from all three models.

The calculated resonant frequencies and mode shapes from the ANSYS model below 1000 Hz are shown in Attachment 3. Reviewing the plots, the quarter wave mode shapes are easily seen for frequencies below about 600 Hz. Once you reach 600 Hz non-axial mode shapes start to intermingle with the axial modes. The MathCad worksheets are not capable of predicting non-axial modes but at these higher frequencies both the low pass crossover and the fiber damping should remove them from being significant issues. The results of this double check are shown in Figure 11.

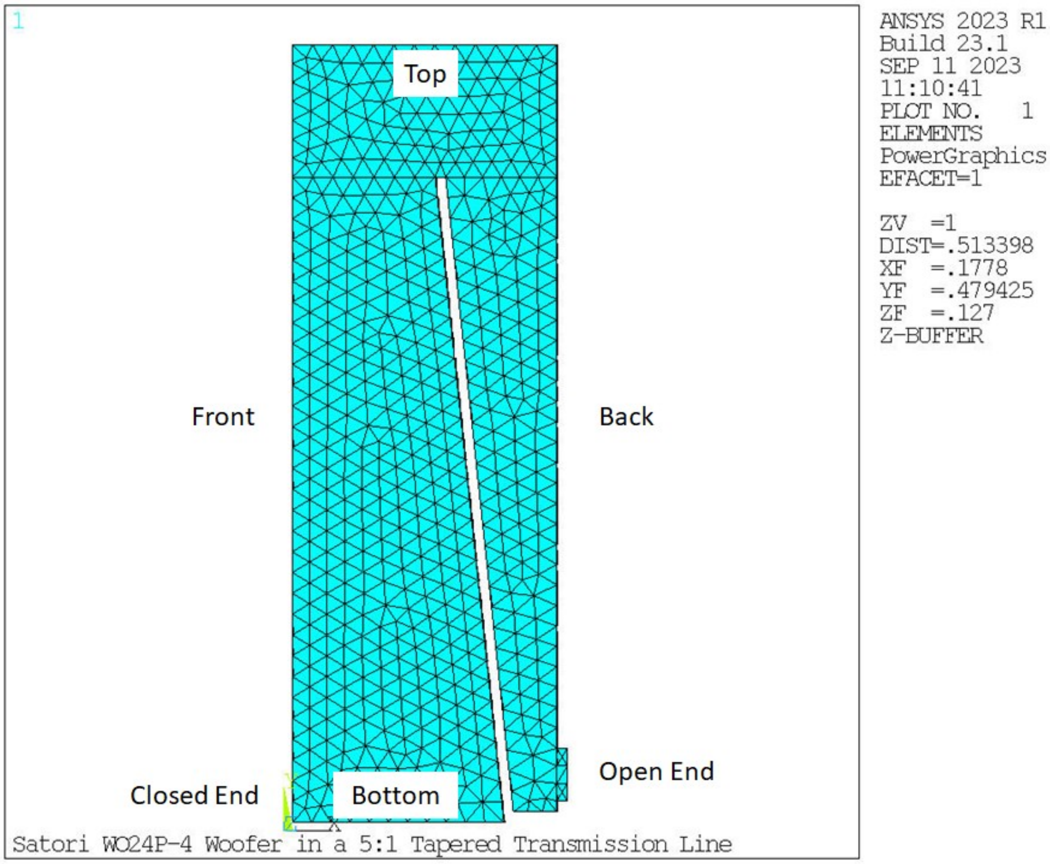
In Figure 11 notice that the ANSYS frequencies are consistently higher than the two MathCad model results, the physical effective length is shorter or the discontinuity at the corners effectively reduces the length. The two Mathcad models, traditional and advanced centerline corner modeling, produce very similar results. The ANSYS model is believed to be closer to the real answer since no assumptions are made with respect to the corner modeling, wavefront shape, or centerline path/length. But taking a step back, the results are all close enough to be used for design without a gross miss in the acoustic SPL predictions from the final TL enclosure simulation.

Figure 11 : Resonant Frequency Checks

				MathCad				MathCad	
ANSYS				Centerline Method				Advanced Centerline Method	
Frequency	Mode		Frequency	Mode	Difference		Frequency	Mode	Difference
35	1/4		33	1/4	5.71%		33	1/4	5.71%
144	3/4		134	3/4	6.94%		137	3/4	4.86%
243	5/4		228	5/4	6.17%		227	5/4	6.58%
340	7/4		321	7/4	5.59%		322	7/4	5.29%
438	9/4		415	9/4	5.25%		413	9/4	5.71%
527	11/4		506	11/4	3.98%		506	11/4	3.98%
605	13/4		597	13/4	1.32%		598	13/4	1.16%
697	15/4		691	15/4	0.86%		690	15/4	1.00%
Hz			Hz				Hz		
			Length	73.2	inches		Length	71.1	inches
			SF_5_1	0.71			SF_5_1	0.71	
			f_tuning	32.8	Hz		f_tuning	33.8	Hz
			Volume	75.4	liters		Volume	71.7	liters

A closer look at the ANSYS results also sheds some light on the behavior of the vibrating air in the TL enclosure, particularly in the corners at the top of the enclosure. Figure 12 contains the side view of the meshed finite element model. Figure 13 plots the normalized pressure profile for the first resonant standing wave, the quarter wavelength mode shape.

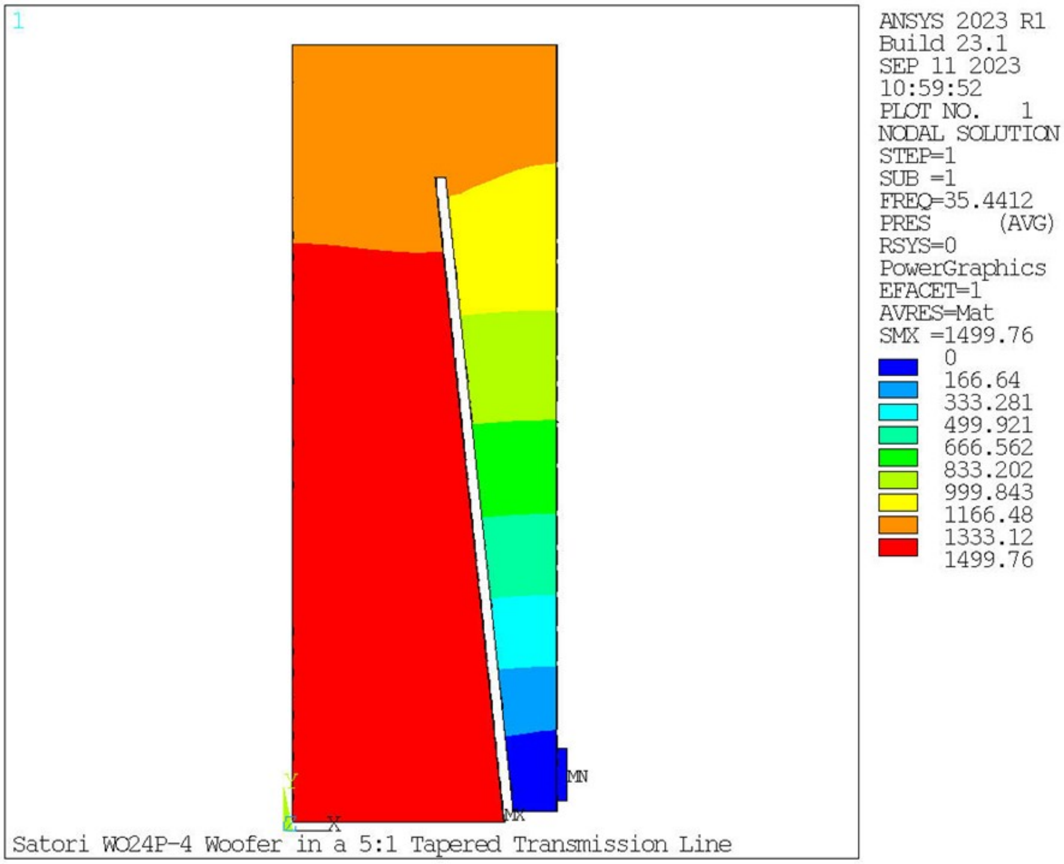
Figure 12 : Meshed Finite Element Model



The finite element model simulated only the air volume inside the enclosure. The walls are assumed to be rigid, and the woofer is not included. In the figure above you can see the tilted internal brace location splitting the internal volume to create the folded tapered geometry. At the bottom of the enclosure a small extension is modeled to represent the exit path through the enclosure's back wall. At the top of the enclosure a 180-degree fold exists, and the oscillating pressure and velocity profiles need to navigate through this discontinuity. At the bottom a 90-degree bend is generated for the vibrating air to exit the TL and enter the listening room.

The pressure contour plot for the first standing wave is shown in Figure 13. This contour plot captures the normalized pressure distribution at the peak of the cycle. Half of a cycle later the pressure values would all be negative. In your mind visualize the pressure profile oscillating positive to negative and back to positive at a frequency of 35.4 Hz. If you were to stretch the geometry out to be straight, then the pressure profile would resemble a quarter of a cosine wave with the maximum pressure at the closed end and the minimum (zero pressure boundary condition) at the open end as expected. It would follow that the velocity profile along the length would look like a quarter sine wave, zero at the closed end increasing to a maximum at the open end.

Figure 13 : Pressure Contours for First Quarter Wavelength Mode Shape



Some features in the pressure contour plot shown in Figure 13 were used to gain insight into the oscillating air velocity distribution in the TL. First, the pressure contours are all normal to the walls of the enclosure, this produces non-planar slightly curved pressure fronts across the line's cross-sectional areas. Reviewing all the resonant frequencies and plotted mode shapes in Attachment 3, this observation can be confirmed for each plot.

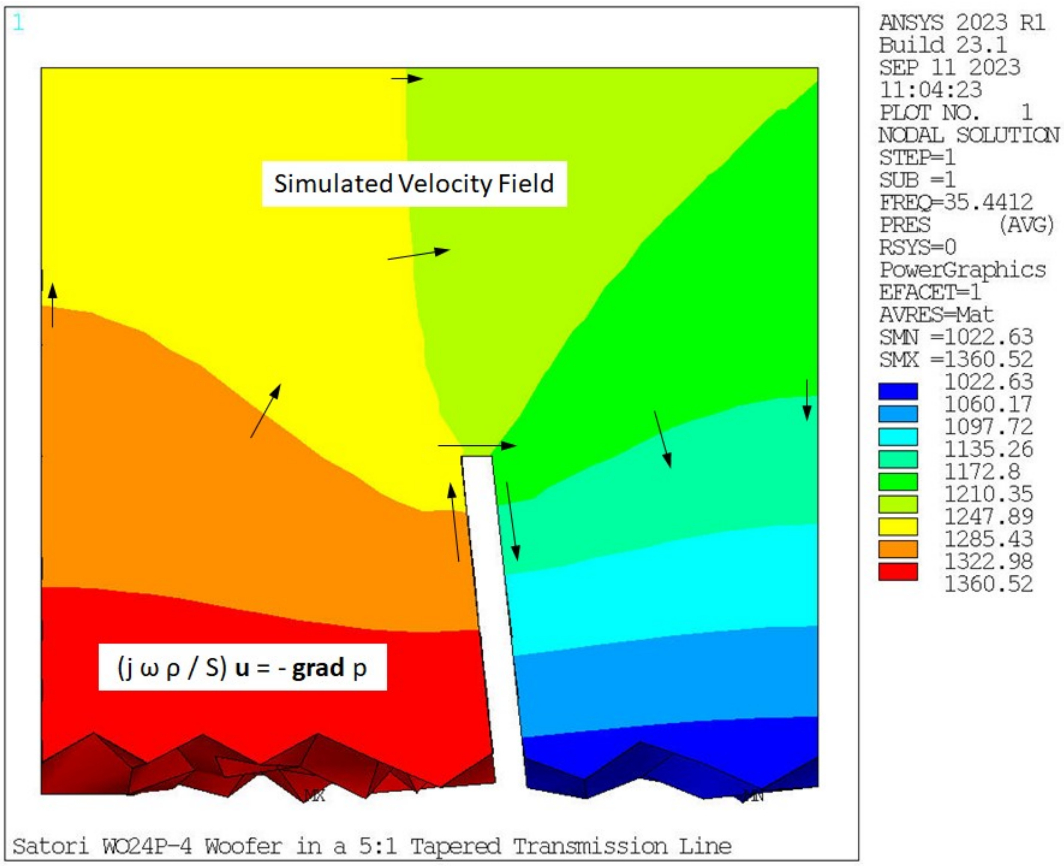
The pressure gradients along the length, across the line's cross-sectional areas, were used to visualize the oscillating velocity profile for each resonant frequency and mode shape. When deriving the 1D differential equation of motion for TLs, the classic 1D wave equation, the momentum equation (Newton's 2nd Law) was applied.

mass x acceleration = Force

$$(j\ \omega\ \rho\ /\ S)\ u(x) = -\ dp(x)\ /\ dx$$

The momentum equation indicates that the gradient of the pressure profile (rate of change of pressure with distance) is related to the air velocity which is normal to the pressure contours. Figure 14 zooms in on the top corner of the TL replotting the scaler pressure contours and then adding a representation of the distribution of air velocity vectors. Again, this is the peak in the cycle, everything is oscillating at 35.4 Hz. Notice that the air velocity vectors are parallel to the enclosure walls and are not a constant magnitude across the cross-sectional areas as they rotate through the 180-degree fold. This is probably the source of the differences in results from various 1D models commonly proposed for representing folds, bends, or other discontinuities in TL enclosures. The 1D models assume a constant pressure and velocity across the cross-sectional area and do not consider the variation seen in Figure 14. To improve the accuracy of 1D models it is not just simply a difference in path length but also the expansion and contraction of the cross-sectional area as it transitions through the discontinuity.

Figure 14 : Simulated Velocity Profile in the Top Corners of the TL



One last point before moving on to other double checks of the 1D model, just to add a little more confusion. The results shown in Attachment 3 are the resonant frequencies and modes shapes of just the air column in the TL enclosure, one of the two subsystems that form the complete TL loudspeaker system. The other subsystem is the woofer itself, a single degree of freedom system with a resonant frequency f_s that is typically the same or close to the enclosure's tuning frequency f_b. When you combine these two subsystems, the final completed system's resonant frequencies shift to bracket the subsystem's resonant frequencies and the mode shapes change, in particular the woofer's resonant frequency and the enclosure's quarter wavelength tuning frequency. These first two subsystem resonances split, producing one lower resonance peak and one higher resonance peak, the double humped electrical impedance curve (just like a bass reflex design) bracketing the woofer's single peak electrical impedance hump. The two electrical impedance humps are the new first two combined system resonances and the woofers f_s and the enclosures f_b should no longer be thought of as system resonances. All the higher quarter wavelength modes will also shift a little higher with less of an impact on the higher modes. This interesting behavior will be the subject of an upcoming article.

Moving on, a second set of double checks were made on the finished speaker system after assembling the woofer and enclosure by measuring the electrical impedance, the near field woofer SPL response, and the near field terminus SPL response of the empty and stuffed TL. The stuffing in the TL was 0.5 lb/ft^3 of polyester fiber for approximately 3/4 of the line's length (closed end up through the bend at the top and halfway down the back of the enclosure). The results of these measurements (dashed red curves) were overlayed on the MathCad predictions (solid red curves) as shown in Figures 15 and 16 respectively for the left speaker (the results for the right speaker were essentially the same). In my opinion, the correlation between measured and calculated results at low frequencies is excellent. Any errors introduced by modeling the TL using MathCad 1D methods do not appear to be significant.

Reviewing the two sets of plots in Figures 15 and 16 from top to bottom, several observations can be made about how the finished TL enclosure is behaving.

Impedance Plot (top plots)

- The enclosure is airtight, this was a concern for the design concept utilizing a bolted enclosure with a foam rubber seal. The measured double humped peaks for the empty TL, Figure 15 top plot, match the MathCad calculation which assumed a perfectly airtight rigid box and the minimum between the peaks was evidence that the quarter wavelength standing wave was generated and supported by the as-built enclosure.
- It is interesting that the higher harmonics, the 5/4 and 7/4 wavelength enclosure resonances, did not generate any significant peaks in the simulated or measured electrical impedance of the empty TL. There was no sign of the higher harmonic quarter wavelength standing waves in either of the impedance plots.
- Adding the 0.5 lb/ft3 of polyester fiber stuffing, Figure 16 top plot, had the expected impact of damping the double hump peaks, the first two system resonances, with the biggest impact on the lower peak.

Woofer Near Field SPL Plot (middle plots)

- The deep null at the tuning frequency in the empty TL results, Figure 15 middle plot, also indicated a well-sealed TL enclosure. Leaks would have led to a shallow and broader dip.
- Up to 400 Hz, the modes correlated well between test and calculated.
- Extra peaks and dips above 700 Hz may be nonaxial resonances, the 3D ANSYS model predicted these modes.
- The 3/4 enclosure resonance, seen in the terminus data, was not evident in the empty TL woofer data while the 5/4 and 7/4 enclosure resonances produced small wiggles. This indicates that the 3/4 wavelength standing wave was weakly excited because the driver was close to the zero-pressure point in the standing wave. Adding stuffing cleaned up these higher harmonic resonances as seen in the middle plot of Figure 16.

Figure 15 : Electrical Impedance, Near Field Woofer. and Terminus SPL <u>Empty</u> TL
solid – calculated, dashed – measured

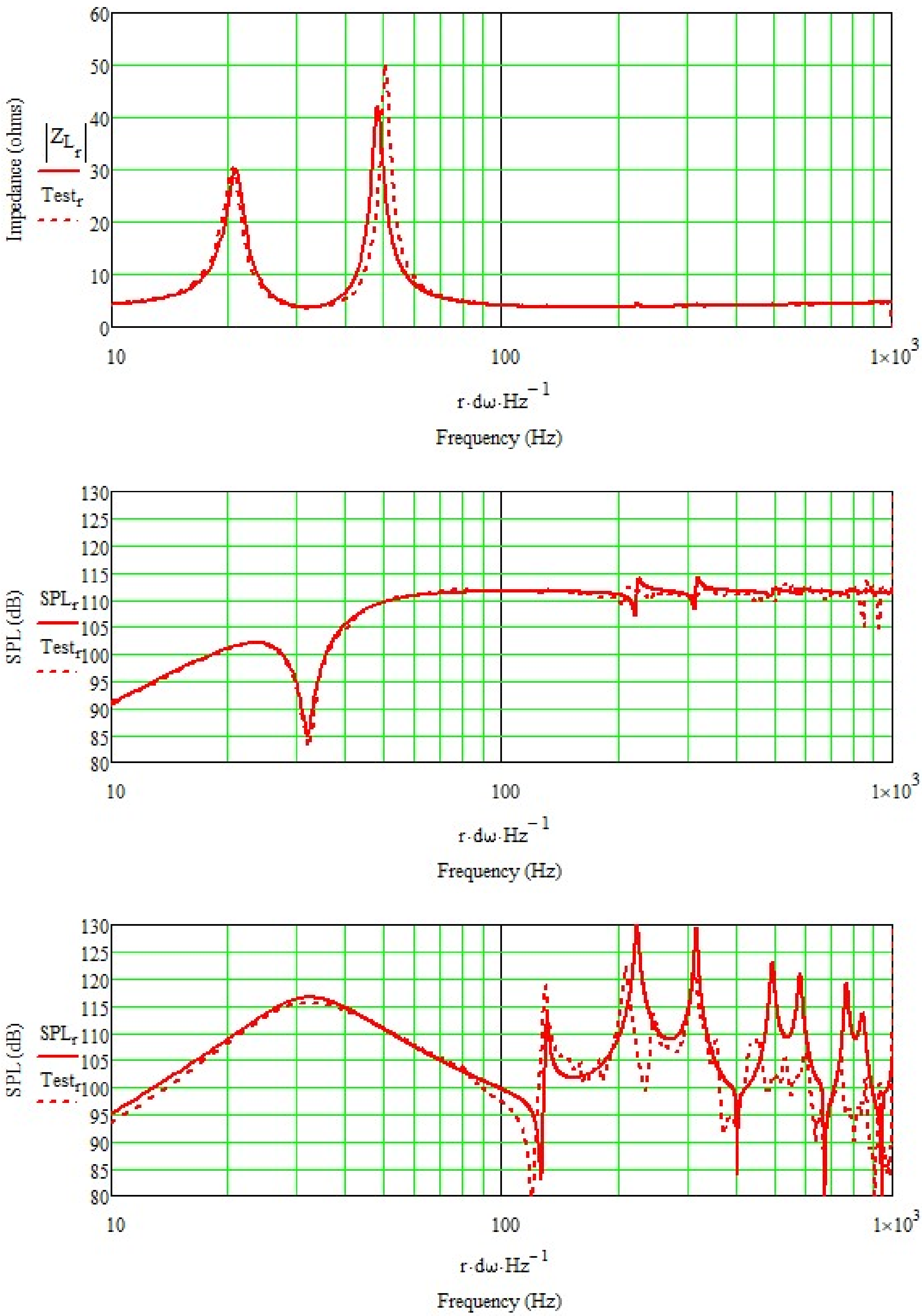
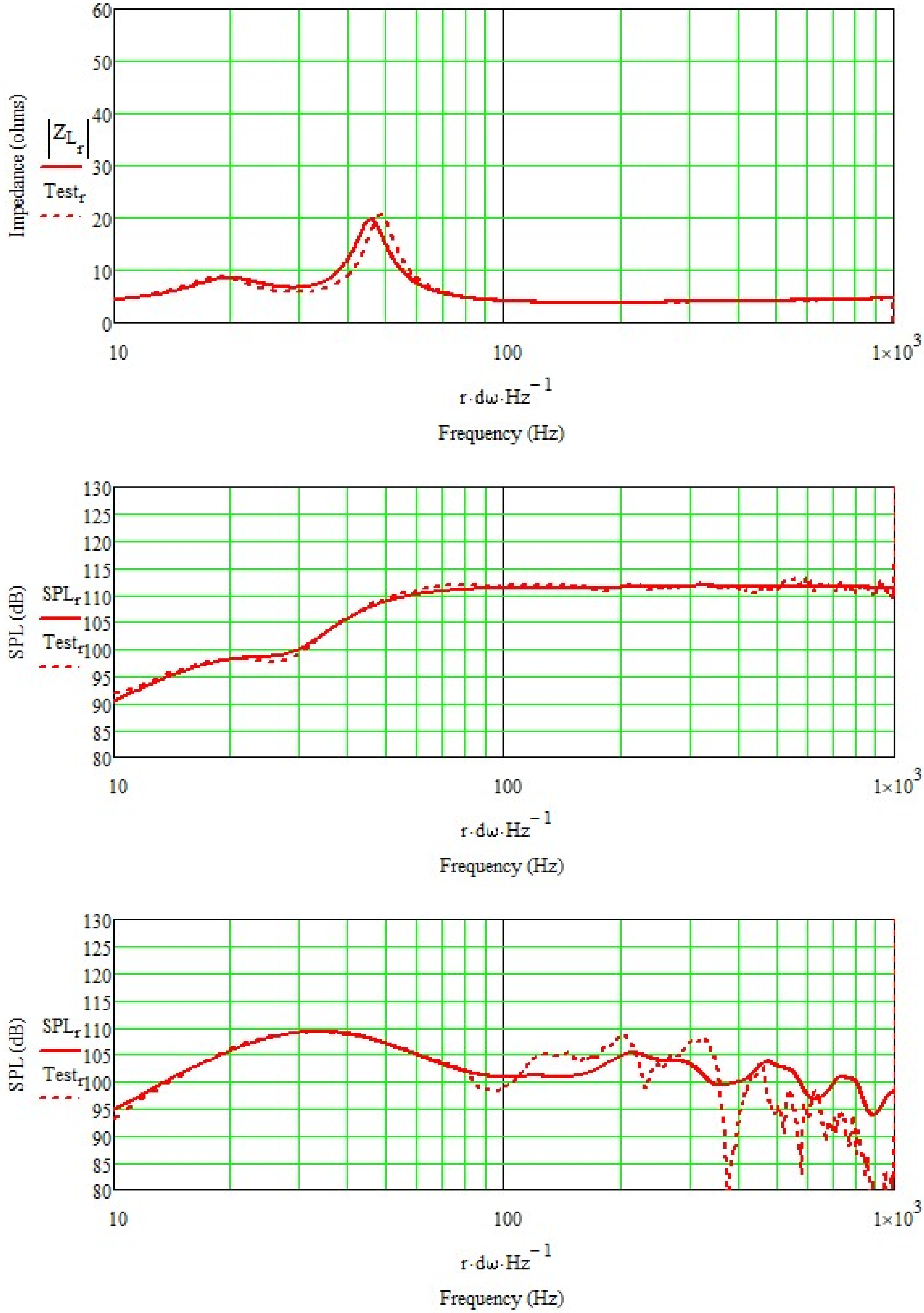


Figure 16 : Electrical Impedance, Near Field Woofer. and Terminus SPL Stuffed TL
solid – calculated, dashed – measured



Terminus Near Field SPL Plots (bottom plots)

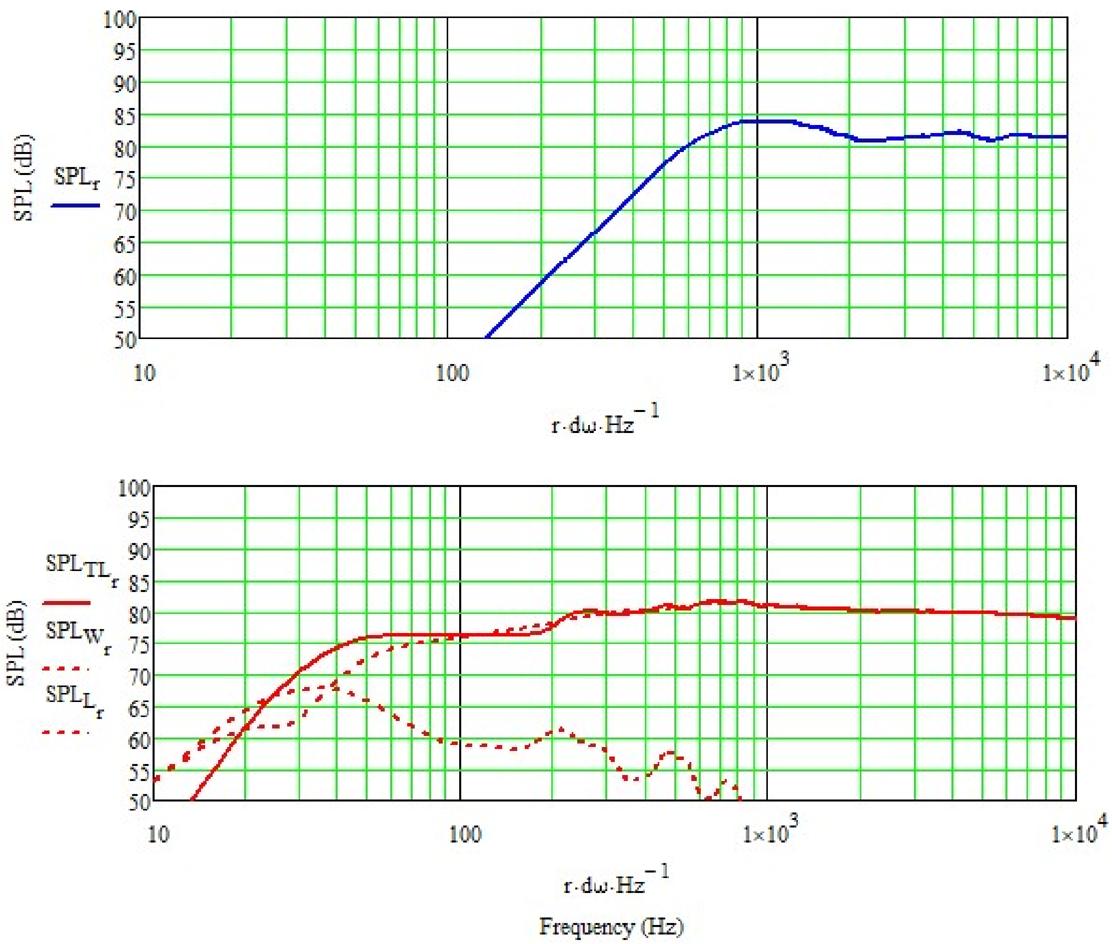
- The woofer was not perfectly positioned to completely cancel the 3/4 wavelength resonance which produced a significant ripple at about 125 Hz in the empty TL results, Figure 15 bottom plot. The wiggle started with a dip followed by a peak which indicated that the woofer was too far from the closed end, $\xi = 0.345$ (> 0.333). If the woofer was too close, less than $\xi = 0.333$, the ripple would start with a peak followed by a dip. The additional offset in the design was less than one inch and was driven by the positioning of the woofer relative to the tweeter which was located at the desired listening height. The 3/4 wavelength mode was not very responsive and easily handled by fiber damping, Figure 16 bottom plot.
- As frequency goes up, the measured axial standing waves were less responsive. Above 400 Hz the measured and calculated SPL responses tended to diverge with the measured rolling off compared to the calculated SPL response. This was more obvious in the stuffed TL results, Figure 16 bottom plot, and initially I was concerned that the fiber damping model was not working. But careful inspection showed the same phenomenon in the empty TL results, Figure 15 bottom plot. There were two potential causes for this observation that immediately came to mind. The foam rubber sheet used as a seal on both side walls of the TL was providing some small damping or the excitation of the higher frequency nonaxial modes, predicted by the ANSYS model, was reducing/syphoning off excitation for the nearby axial modes. I am leaning towards the latter as the most likely candidate for explaining the observed differences.

Overall, in my opinion, correlation between the 1D MathCad simulations and the measured electrical impedance and near field SPL responses over the frequency range that the TL enclosure produces bass output was excellent.

Crossover Designs :

The drivers' calculated SPL responses at three meters are shown for the woofer and tweeter in Figure 17 without any crossover. The important feature to be considered in Figure 17 is the baffle step and the woofer's low frequency SPL value of 76 dB compared to the tweeter's SPL value of 81 dB at high frequencies.

Figure 17 : Woofer and Tweeter SPL Anechoic Responses at 3 meters w/o Crossover

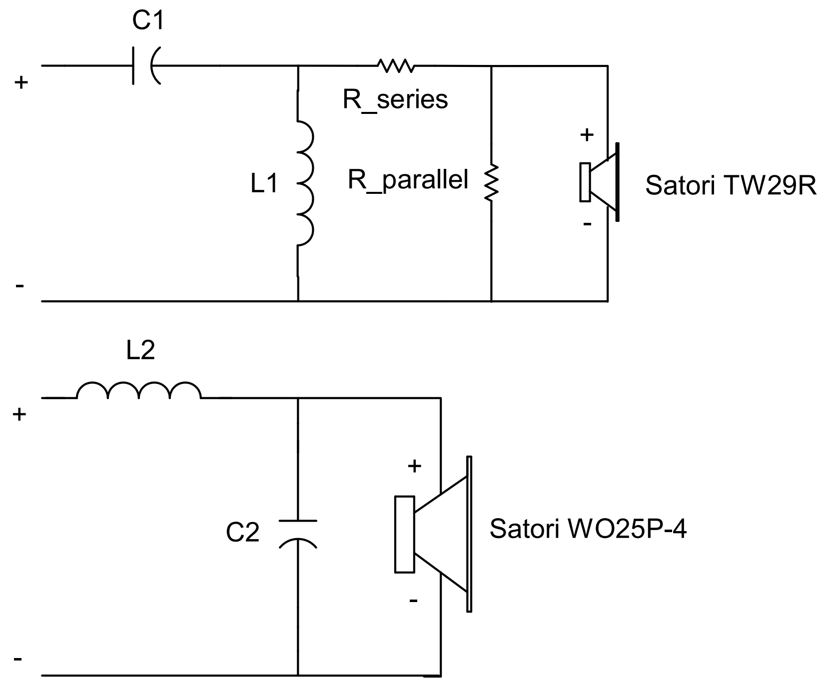


Two crossovers were designed for this TL speaker, there are probably many more possible crossovers depending on the listener's voicing taste. A passive crossover along with the MathCad simulated SPL response are shown in Figure 18. The settings for a second active crossover and the MathCad simulated SPL response are shown in Figure 19. Both crossovers were implemented and the sonic performance of the two was very similar.

Both crossovers address the baffle step that occurs between 100 and 1000 Hz in the filter design. For the passive low pass crossover, a larger than anticipated inductor was inserted to start rolling off the SPL at the baffle step frequency and then the paralleled capacitor completed the second order 12 dB/octave filter. For the active low pass crossover, a simple low frequency first order 6 dB/octave filter was applied. In both the passive and active crossovers, the high pass used a second order 12 dB/octave Butterworth filter at 2100 Hz and 1600 Hz respectively. Both crossover designs have the drivers connected in phase and include approximately 10 dB of attenuation for the tweeter to match the woofer's low frequency output while producing the desired downward high frequency slope. For a brighter or darker sound, the 10 dB attenuation can be reduced or increased respectively by changing the resistors in the passive version or the attenuation setting in the active version of the crossover.

The last results presented from the crossover design are the calculated vertical polar response plots shown in Figures 20 and 21. In both polar plots there is a broad lobe on the axis of the tweeter. Notice in the right side of Figure 1, the woofer is set back in the baffle from the tweeter by an estimated difference in the acoustic centers of the drivers. If this is an error the main axis of the lobe might tilt up or down slightly, but the on-axis SPL response will be essentially the same at the listening position. Also notice that there is a null formed below the axis of the tweeter which might help reduce the impact of floor reflection (the floor bounce dip).

Figure 18 : Passive Crossover SPL Response at 3 meters



C1 = 18 uF (Solen Capacitor)
L1 = 0.33 mH (ERSE Perfect Lay 14 AWG Inductor, R = 0.1 ohm)

R_series = 2.5 ohm (Mills Resistor)
R_parallel = 1.5 ohm (Mills Resistor)

C2 = 36 uF (Solen Capacitor)
L2 = 3.5 mH (ERSE Super Q 18 AWG Inductor, R = 0.81 ohm)

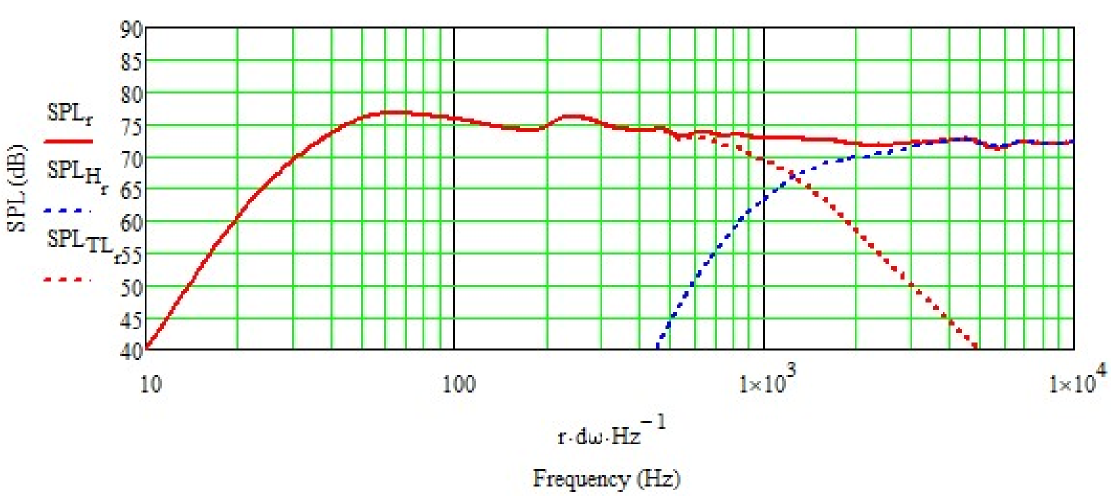


Figure 19 : Active Crossover SPL Response at 3 meters

Low Pass : 1st order Butterworth at 200 Hz

High Pass : 2nd order Butterworth at 1600 Hz in Phase
10 dB attenuation applied to the Tweeter

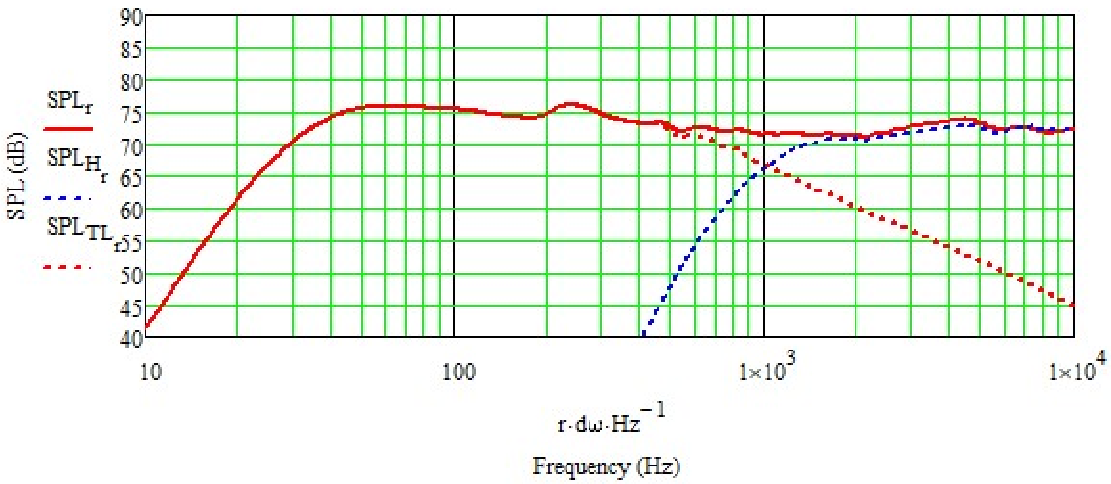


Figure 20 : Vertical Polar Response for the Passive Crossover

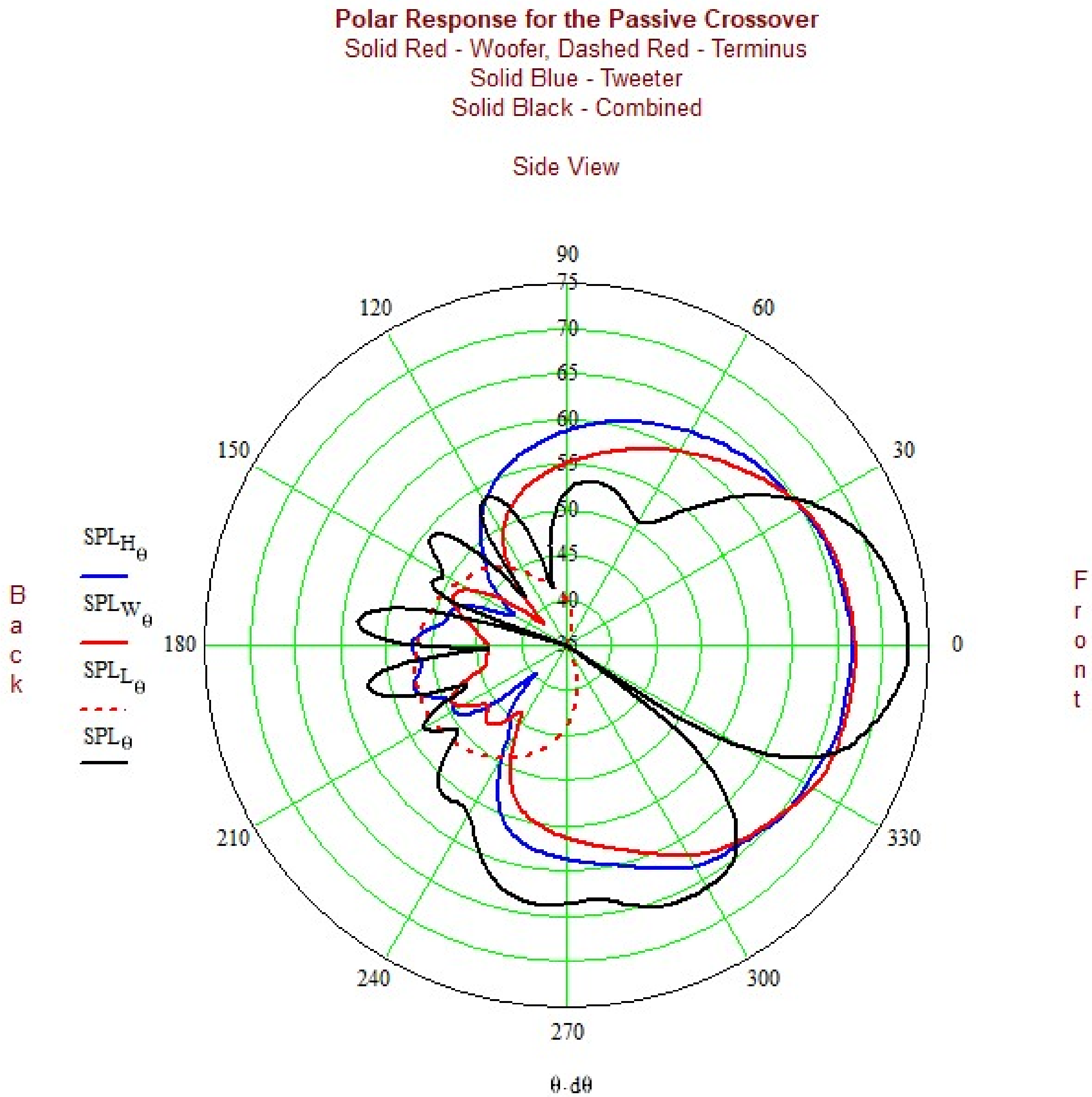
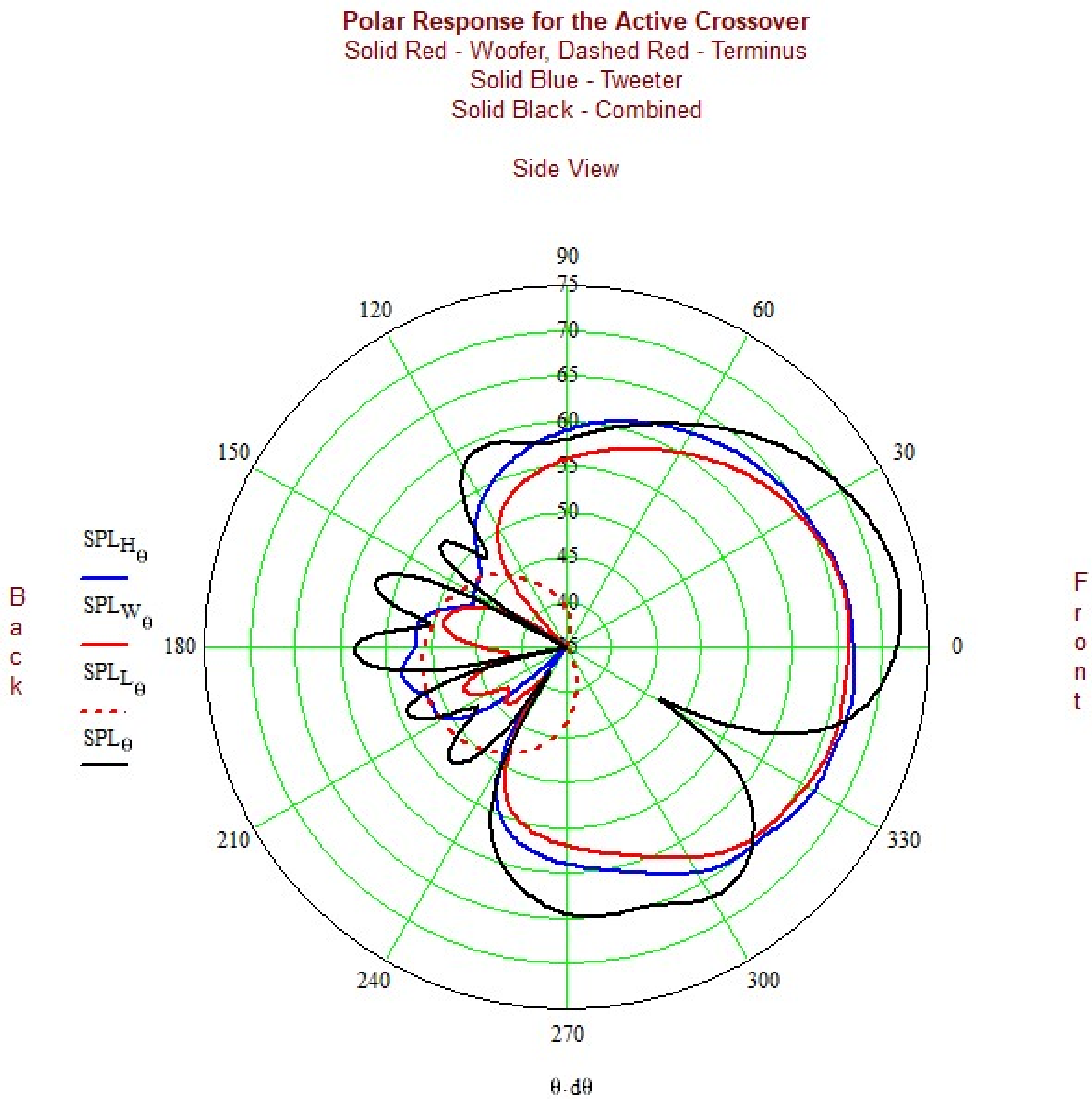


Figure 21 : Vertical Polar Response for the Active Crossover



Final Measurements :

Once the speakers were stuffed with polyester fiber and assembled, they were moved out of the basement workshop and upstairs into my listening room. Measurements at a 1 m distance were performed using the Omnimic software for the completed speaker system and individually for the woofers and tweeters. Both crossovers were tested, the SPL results were postprocessed using 1/12 octave smoothing and then saved as text files. The measured SPL responses were imported into MathCad and overlayed on the calculated SPL responses. These results are shown in Figures 22 through 29 and discussed in the following paragraphs. The raw Omnimic SPL measurement curves are also included as Attachment 4.

Figures 22 and 23 contain the calculated anechoic SPL responses overlayed on the in-room measured SPL responses. The room introduced some additional peaks and dips as expected. The most significant result was the extension of the measured bass output which goes almost an additional 10 Hz lower compared to the anechoic calculated roll off. The performance of both crossovers was very similar, which was also expected.

Figures 24 and 25 contain calculated SPL responses with carpeted floor and drywall rear wall boundary conditions overlayed on the in-room measured SPL responses. The additional bass extension was now picked up by the MathCad results along with a floor bounce cancellation at about 200 Hz. The floor bounce was not as obvious in the measured results, it was probably less pronounced due to the 1/12 octave smoothing. Many of the peaks and dips present in the in-room measurement were now seen in the calculated SPL response curves.

Figures 26 and 27 show the calculated and measured SPL responses of the woofer in the TL enclosure. With the applied boundary conditions in the MathCad models, the rolling peaks and dips lined up nicely between 200 Hz and 3000Hz. The different crossover frequencies and slopes can also be seen in the woofer's roll off SPL output above 500 Hz. However, between 3000 and 5000 Hz an unpredicted broad additional hump was present in the measured SPL data. Reviewing the manufacturer's datasheet, a broad woofer resonance is shown occurring across this frequency range. One advantage of the passive crossover was the 2^{nd} low pass slope which almost eliminated the impact of this peak as seen in Figure 22. The 1^{st} order low pass active crossover allowed a little of this peak to influence the measured system SPL curve as seen in Figure 23. Listening to these two crossovers, I did not hear a significant difference in the speaker's performance so addressing the woofer's measured hump between 3000 and 5000 Hz may not to be necessary.

The active low pass crossover settings could be tweaked some more to address this unpredicted hump (one of the mentioned short comings of the linear MathCad models). This is an advantage of an active system, on the fly electronic adjustments are easy without needing to buy a variety of additional expensive passive circuit components. The passive second order low pass filter adequately suppressed the unpredicted hump. A little clearer understanding of the impact of this woofer resonance can be seen in the raw measurement data contained in Attachment 4. Regardless of the crossover used, the measured tweeter SPL curve was reasonable consistent above 2000 Hz (bottom plot on each page). But in the system SPL plots, the woofer's resonance was seen as a 1- or 2-dB broad rise in the active crossover SPL results that was not present in the passive crossover results.

Swapping between the passive and active crossovers takes a few minutes of reconfiguring the cables. Listening for differences in performance was limited to significant changes. The differences between the two crossovers were subtle at best and both seem to do a good job, I could live long term with either crossover option.

Finally in Figures 28 and 29 the calculated and measured tweeter SPL responses were overlayed for both crossovers. The MathCad calculated SPL responses contained a significant number of ripples due to the modeled boundary conditions. Windowing automatically done by the Omnimic software eliminated the influence of the room at higher frequencies producing a much smoother measured SPL response. Also notice that the broad peak above 3000 Hz was not seen which was further confirmation that it was produced by the woofer.

Reviewing the results presented in Figures 22 through 29 showed that the accuracy of the calculated SPL responses correlated well with the in-room SPL measurements. In-room influences will always interact with a perfectly designed flat SPL response curve hence I try not to obsess too much over 1- or 2-dB calculated ripples. In this case, the results of the anechoic models were extended lower in frequency by the room while not being totally ruined in the pass band. In general, the shape of the final SPL response was always going to be strongly influenced by the room, no avoiding it, so the speakers may sound a little different in various positions in my room or if placed in a completely different room.

Figure 22 : Anechoic Calculated and In-Room Measured SPL Response at 1 m w/ Passive Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

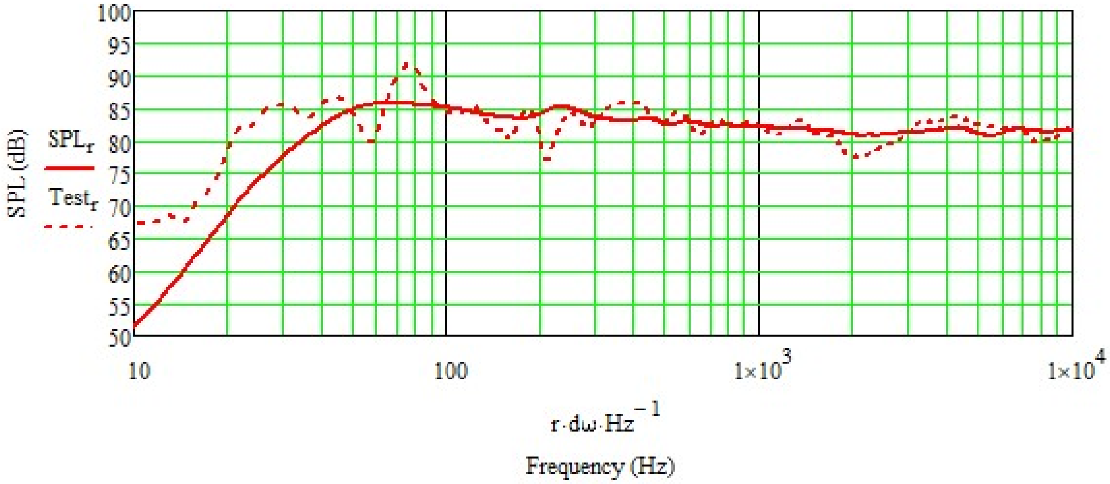


Figure 23 : Anechoic Calculated and In-Room Measured SPL Response at 1 m w/ Active Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

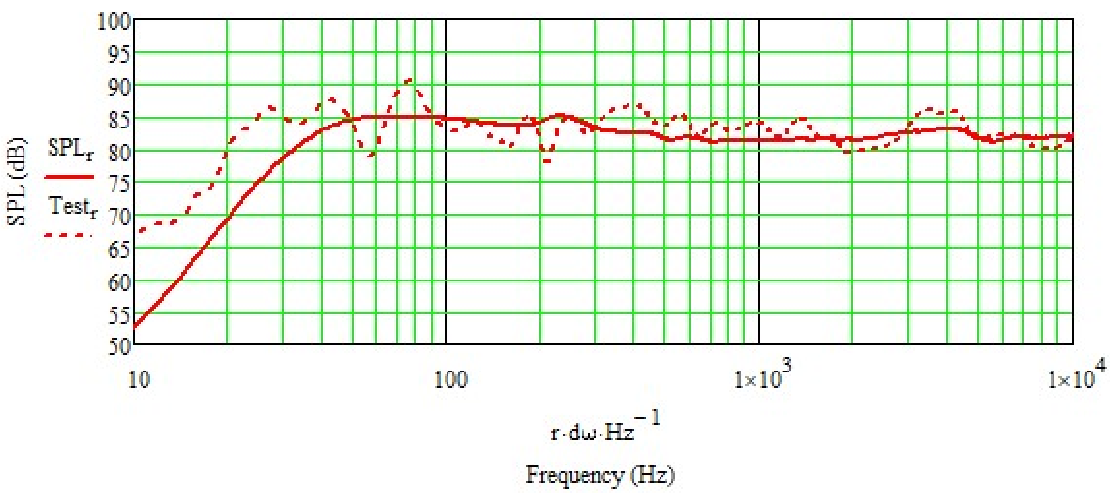


Figure 24 : Calculated and Measured In-Room SPL Response at 1 m w/ Passive Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

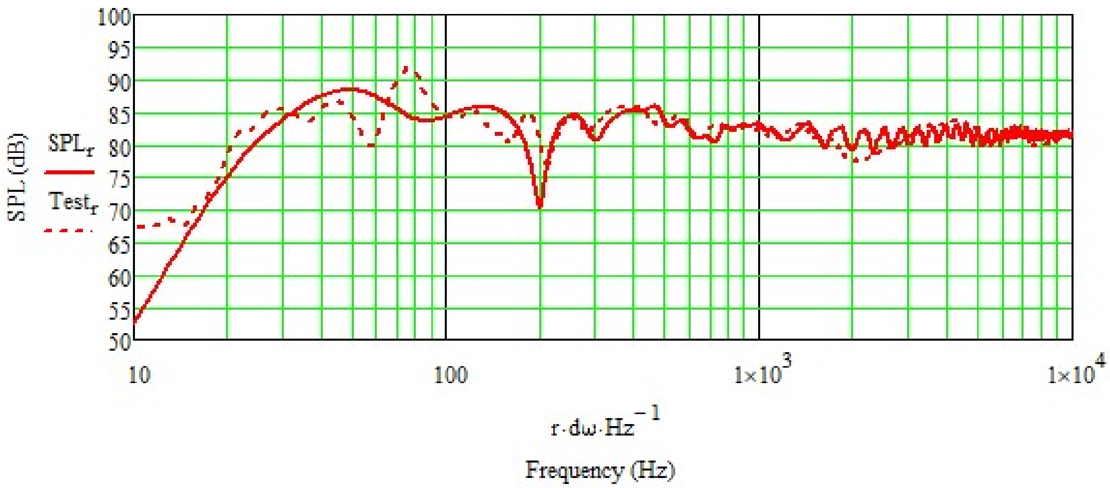


Figure 25 : Calculated and Measured In-Room SPL Response at 1 m w/ Active Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

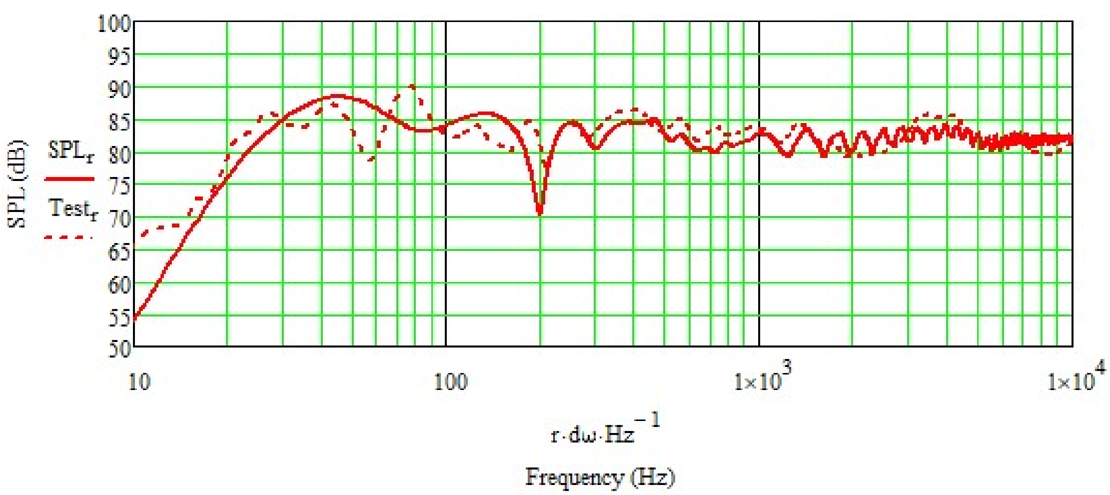


Figure 26 : Calculated and Measured In-Room Woofer and Terminus SPL Response at 1 m w/ Passive Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

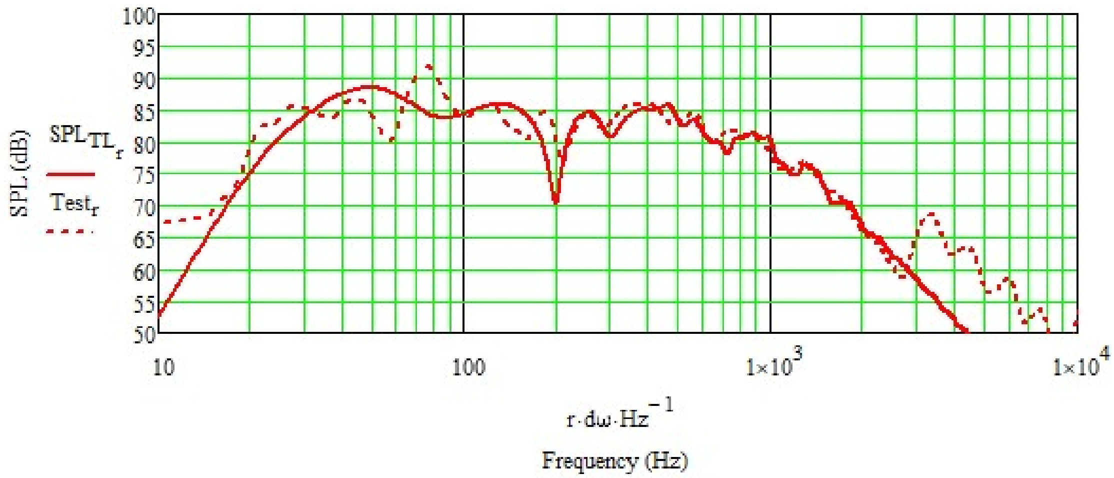


Figure 27 : Calculated and Measured In-Room Woofer and Terminus SPL Response at 1 m w/ Active Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

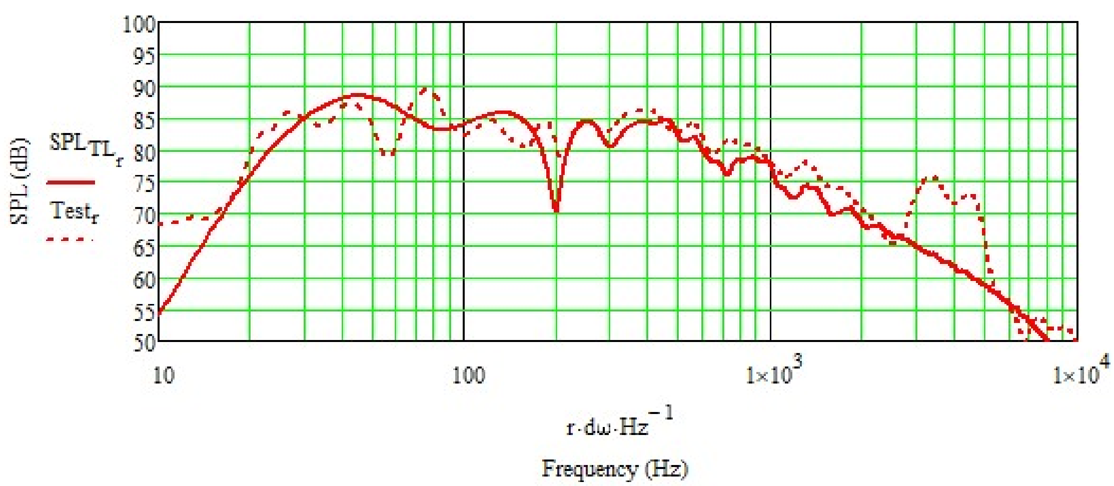


Figure 28 : Calculated and Measured In-Room Tweeter SPL Response at 1 m w/ Passive Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response

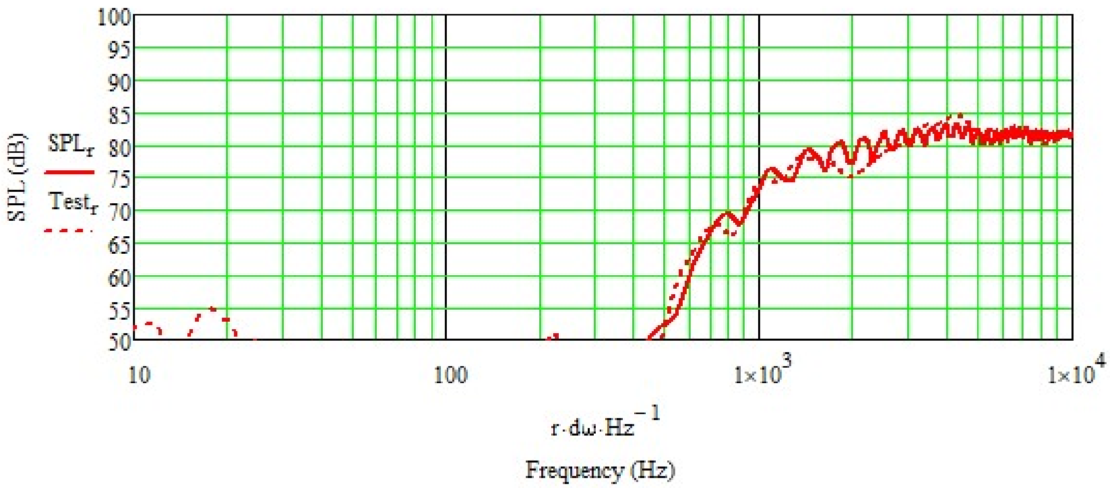
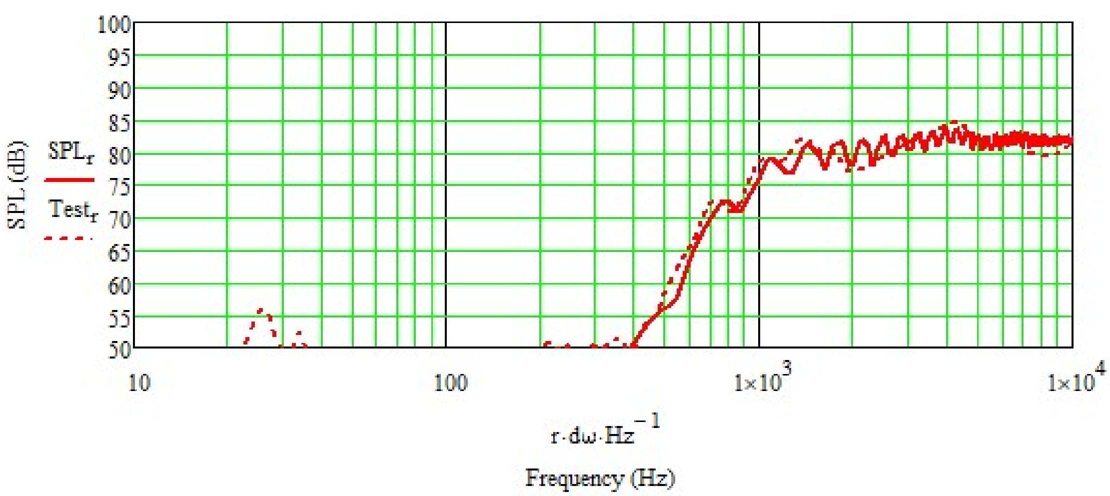


Figure 29 : Calculated and Measured In-Room Tweeter SPL Response at 1 m w/ Active Crossover

Solid - Calculated SPL Response
Dashed - Measured SPL Response



Conclusions :

There were two primary goals of this design effort. First an upgrade to the MathCad worksheets used to design TL loudspeakers (actually, any boxed speaker) and second to design and build a TL speaker system with excellent sonic performance. In my opinion, significant strides have been made to achieve both goals and the results can now be heard in my listening room.

The outcome of the first goal was a set of TL design worksheets that accommodate multiple drivers crossed either actively or passively. The box designs utilize a geometry template so physically buildable enclosures are always considered. Anechoic predictions were used to juggle the enclosure design variables to achieve a desirable SPL response. As a last step in the design cycle, room boundary conditions were applied to estimate the room's impact on the anechoic SPL response. The correlations shown in Figures 24 and 25 were the best I have achieved to date. However, there is still more work that can be done on the model to improve the match between calculated and measured SPL responses.

The second goal of excellent sonic performance was harder for me to quantify. The speaker produces tight deep bass when required, the bass output is articulate enough to easily separate an acoustic bass and a kick drum in jazz trio recording. When bass is not called for the speaker's low frequency output is silent, there is no false bass bloom or boom commonly heard in poorly designed commercial speaker systems. But this is only my opinion since only one other person has heard them. The feedback provided was positive, but he is not really an audiophile, and his comment was that they were very clean and detailed. Unfortunately, I live in an audio vacuum without the opportunity to hear a large variety of other audiophile speaker set-ups either in dealer show rooms or at local DIY audiophile gatherings. I believe that on good recordings with a prominent bass line these TL speakers perform very well, again only my opinion.

As always, comments and suggestions are welcomed and appreciated. Discussing TL design theory, building, and performance, is all part of this obsessive hobby for many people sucked down the rabbit hole of this somewhat exotic style of speaker enclosure.

Future Work :

Additional work is still planned for using this speaker system to further upgrade the MathCad TL worksheets. Improving the calculated and measured SPL curve correlation is an objective, better understanding of a few of the dips and peaks not predicted is high on the list. Improving the acoustic impedance modeling at the open end is another possible advance, but I am not sure if this will be a significant and observable upgrade. Better modeling of corners and discontinuities using the ANSYS finite element model as a guide is of great interest and has significant improvement potential. And finally, probably the biggest advance will come by substituting acoustic foam for the polyester fiber and deriving an appropriate damping model, this was really the main reason for the thread rod construction method used to build these TL enclosures. Commercial TL manufacturers almost all use acoustic foam to line the path since it gives an easily repeatable and consistent final production transmission line speaker system.

References :

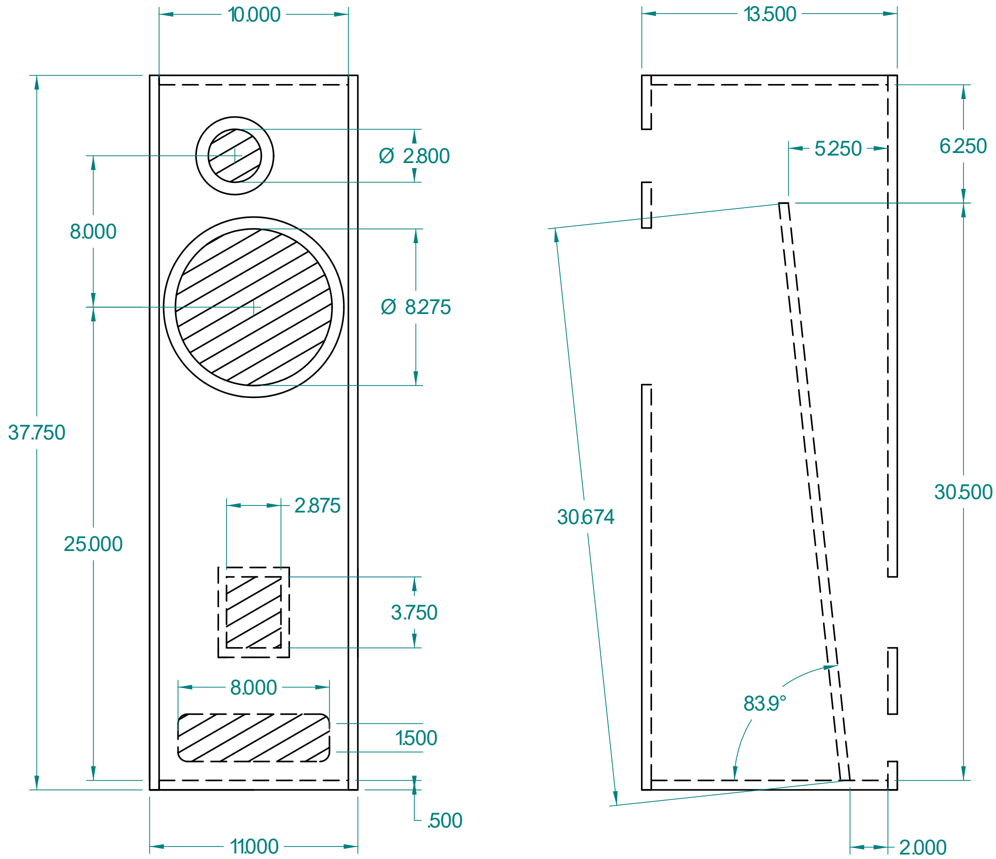
1. Classic Transmission Line Enclosure Alignments, by Martin J. King, 12/27/2021 http://www.quarter-wave.com/TLs/TL_Alignments.pdf

2. The Loudspeaker Design Cookbook 3rd Edition, ©1987, by Vance Dickason.

3. ANSYS Student Version 2023 https://www.ansys.com/academic/students/ansys-student

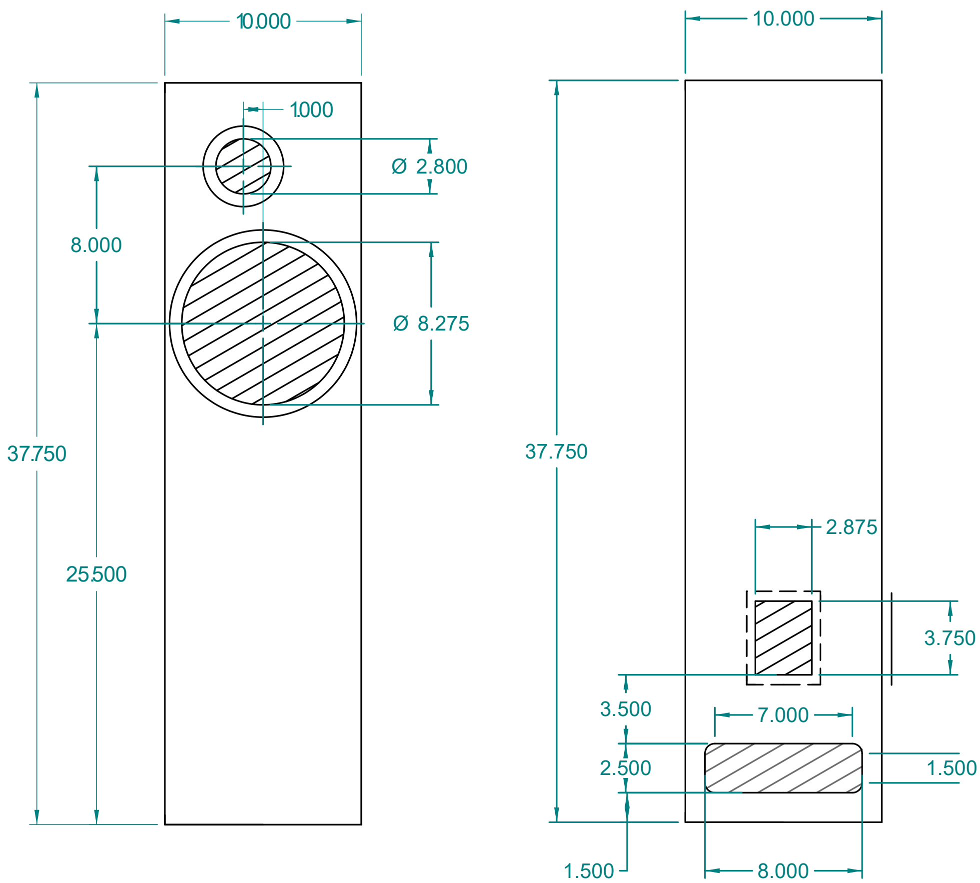
Attachment 1 : Design Sketches

Layout (inches)



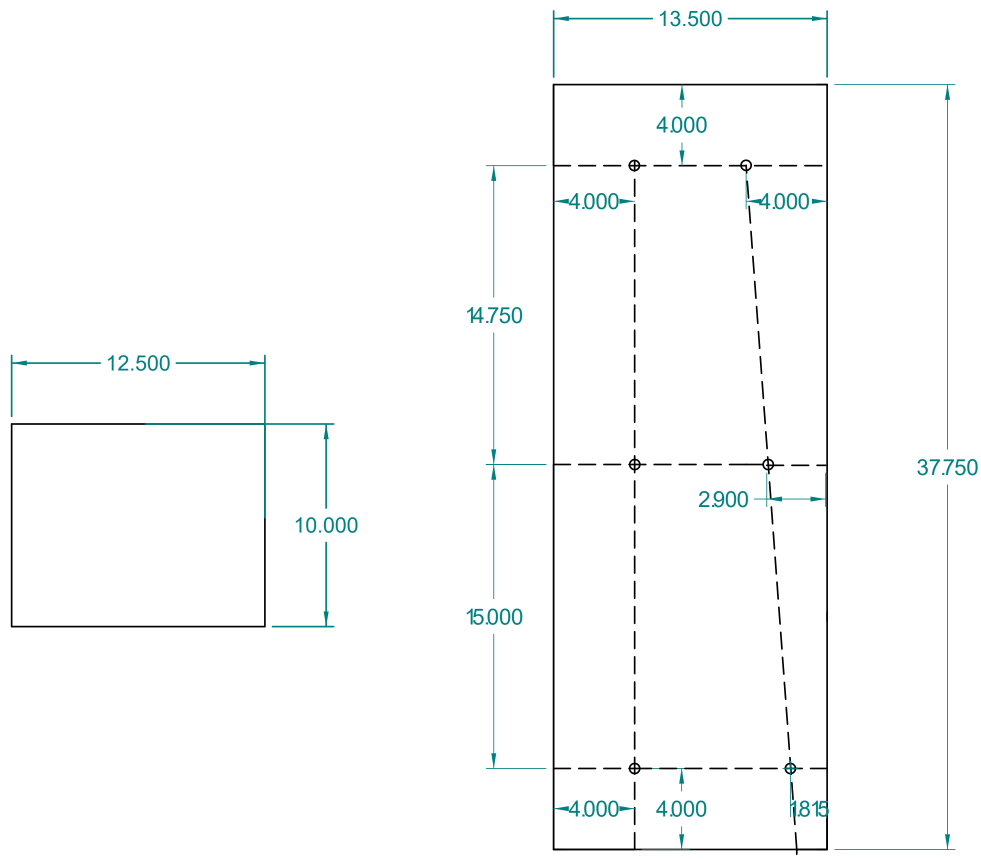
All material 0.5-inch-thick Maple plywood from Lowes. The cross hatched regions represent holes and the outlined perimeters the edges of mounting flanges.

Front and Rear Baffles (inches)



Front Baffles Made as Mirror Images

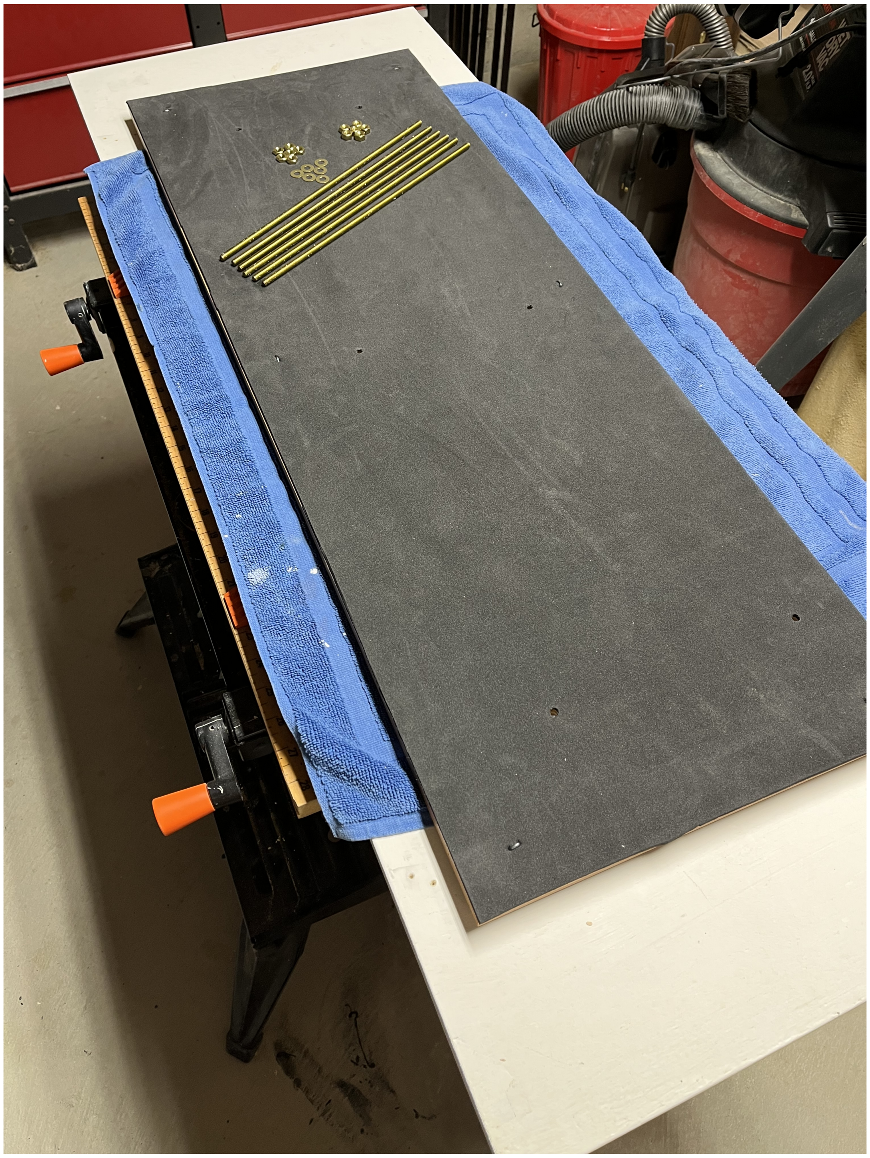
Top, Bottom, and Side Panels (inches)



Side Panels made in Mirror Images with Holes for the Threaded Rods

Attachment 2 : Build Pictures

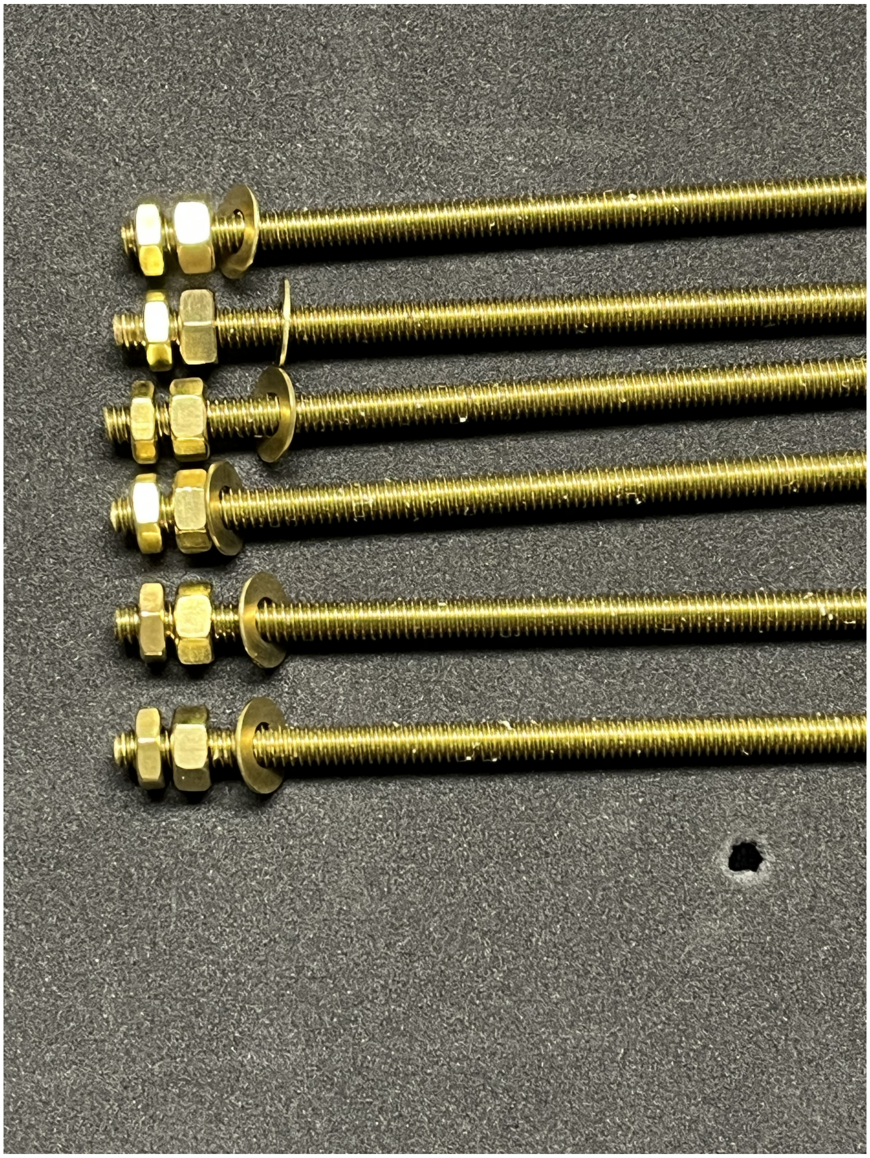
Speaker Side with Foam Sheet Gasket Attached and the Six Threaded Rods.



Two 4' x 8' x 0.5" thick sheets of birch finished plywood from Lowes or Home Depot.

EPDM non-adhesive sponge foam 80" x 17" x 1/8" thick sheet from Amazon.

Brass Threaded Rods, Washer, Nut, and Jam Nut.



Brass threaded rod, 1/4” x 20 thread size, one foot long - 12 pieces

Brass hex nut, 1/4” x 20 thread size - 24 pieces

Brass thin hex nut, 1/4” x 20 thread size - 24 pieces

Brass washer for 1/4” screw size, 0.26” ID and 0.562” OD - 24 pieces

All parts purchased from McMaster-Carr

Center Section Added.

Notice extra bracing of the woofer cut out, at the top of the dividing panel to control the angle, and at the base of the dividing panel to set the final taper geometry. These additional parts are not accounted for in the MathCad or ANSYS models. Six threaded rods are used per speaker to clamp the assembly and create an airtight seal.

Clamped Speaker.

Drivers Wired and Installed.

The drivers are not recessed into the front baffle, that is beyond my limited woodworking skills.

Disassembled and Stuffed with 0.5 lb/ft^3 of Polyester Fiber

Rubber feet and 14 AWG speaker wire from Parts Express

Polyester fill from Jo-Ann Fabrics

Finished Speaker Front View

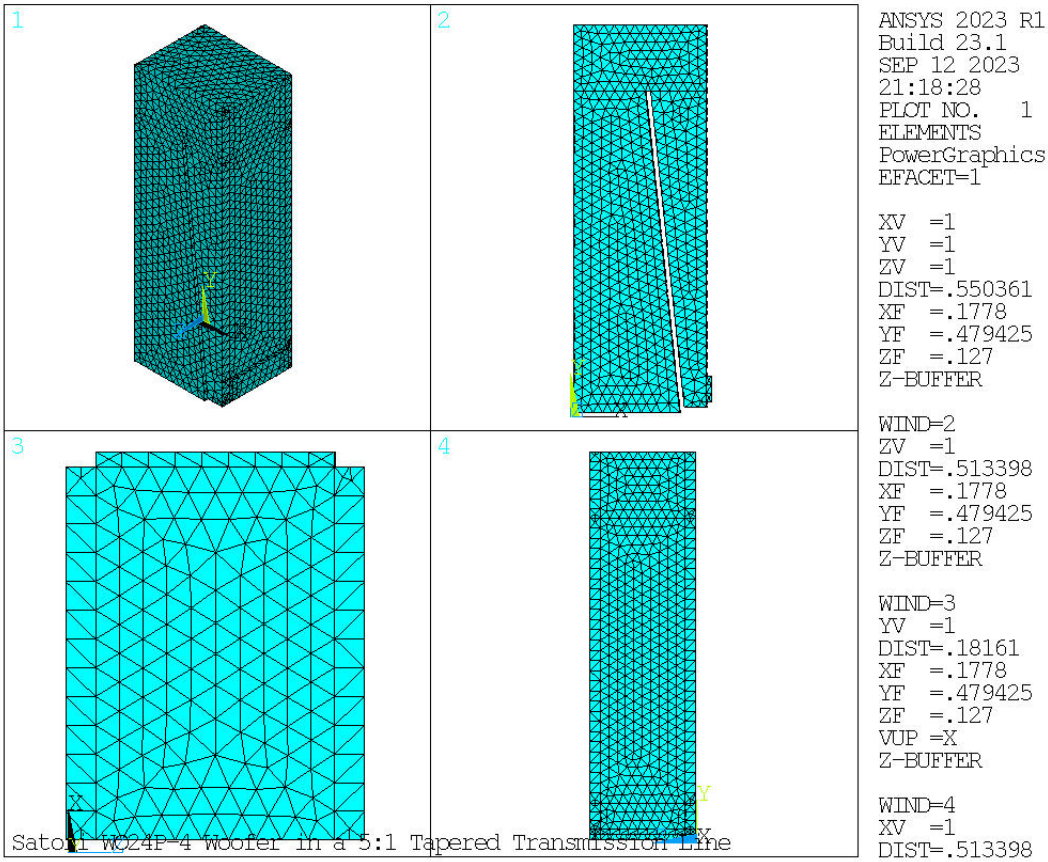
Satori WO24P-4 and TW29R from Meniscus Audio

Finished Speaker Back View

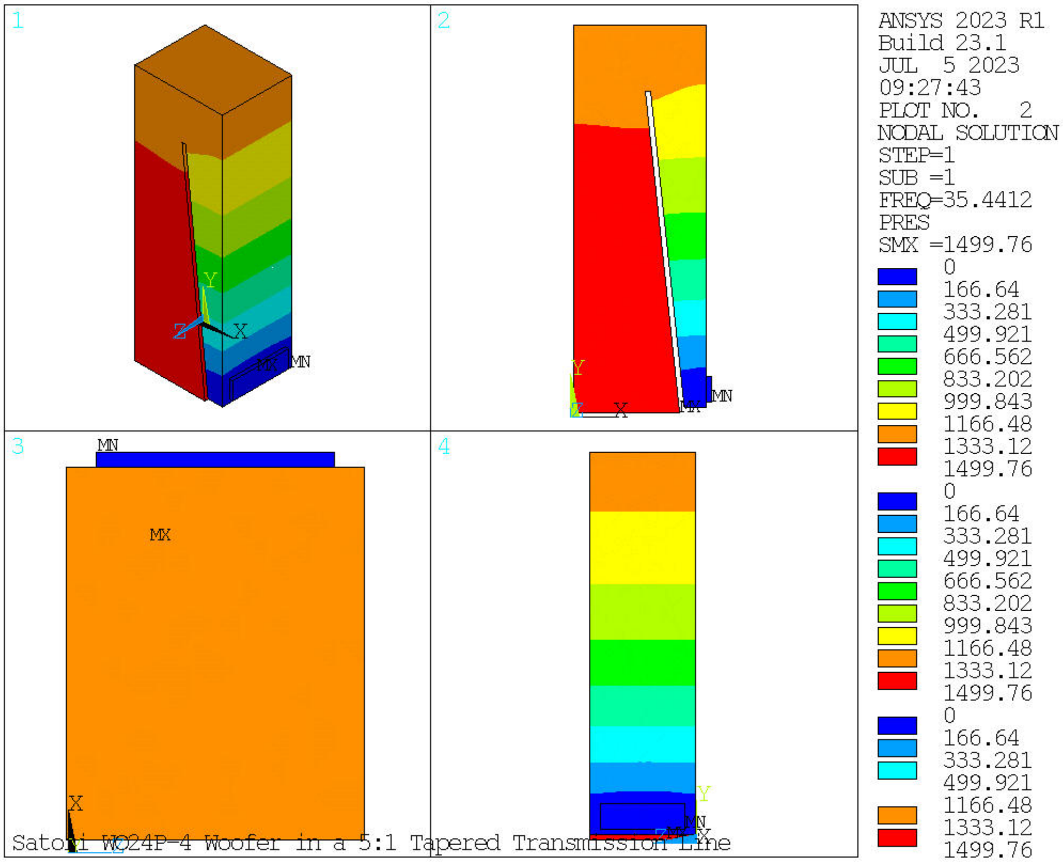
Terminal cup from Parts Express

Attachment 3 : ANSYS Model Resonant Frequencies and Mode Shapes

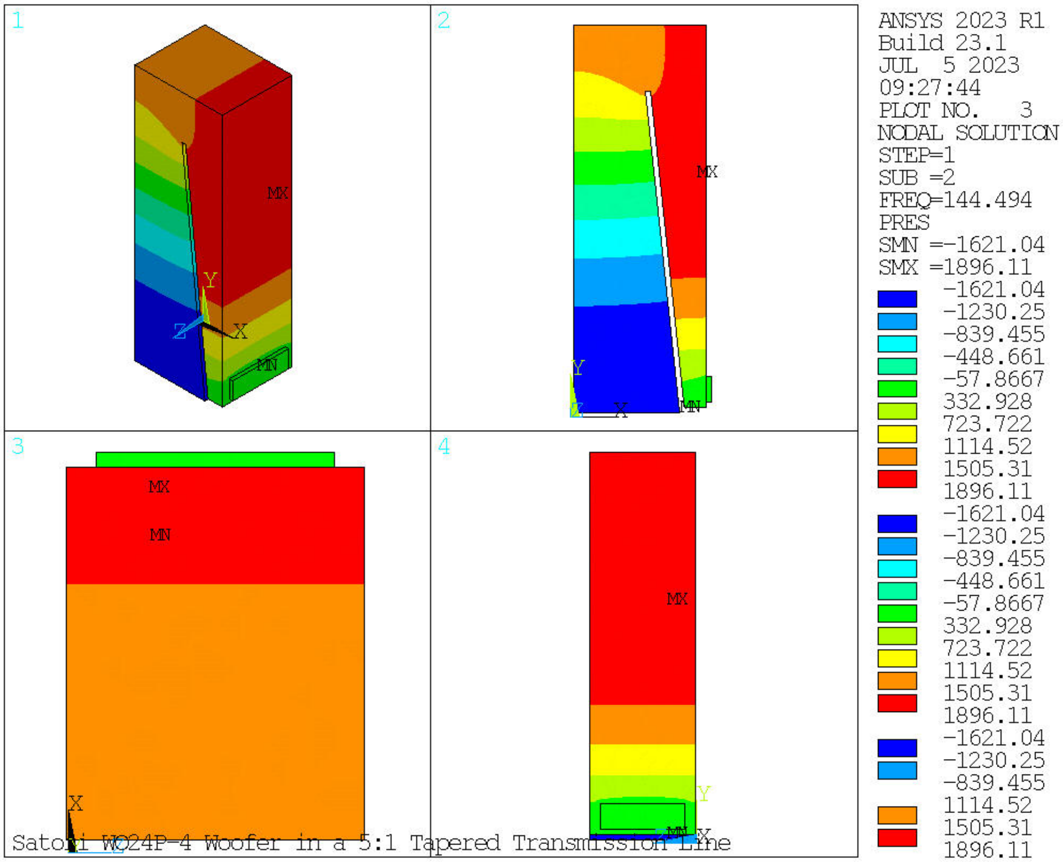
Meshed Geometry



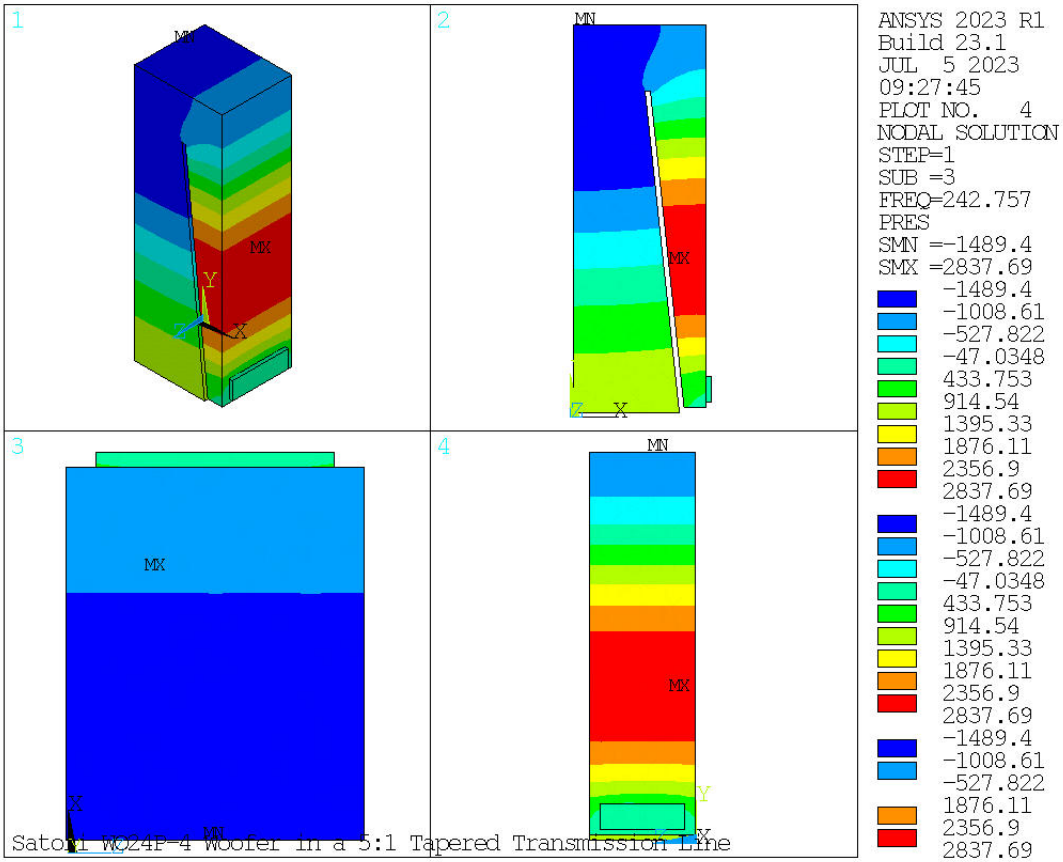
Model of the air volume inside the TL enclosure (isometric and three axis views). Enclosure walls assumed to be rigid and the boundary condition at the open end is zero pressure (meaning the slope of velocity profile is also zero).



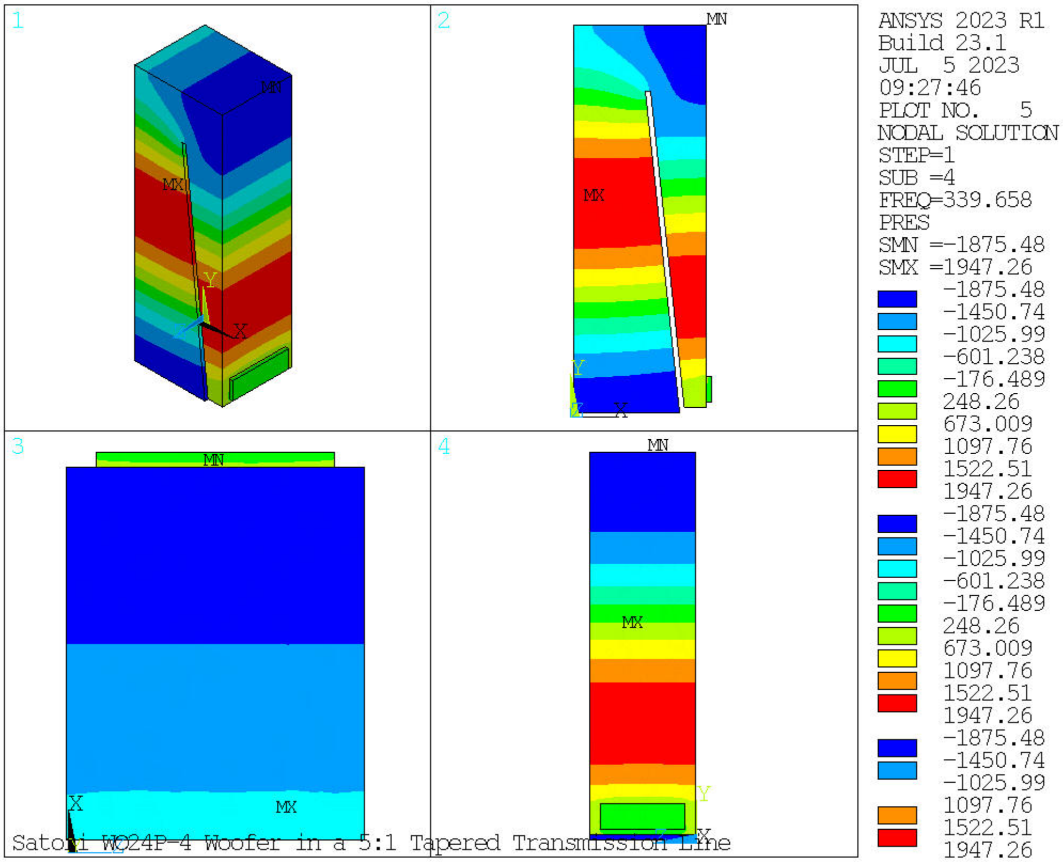
First quarter wavelength mode at 35.4 Hz.



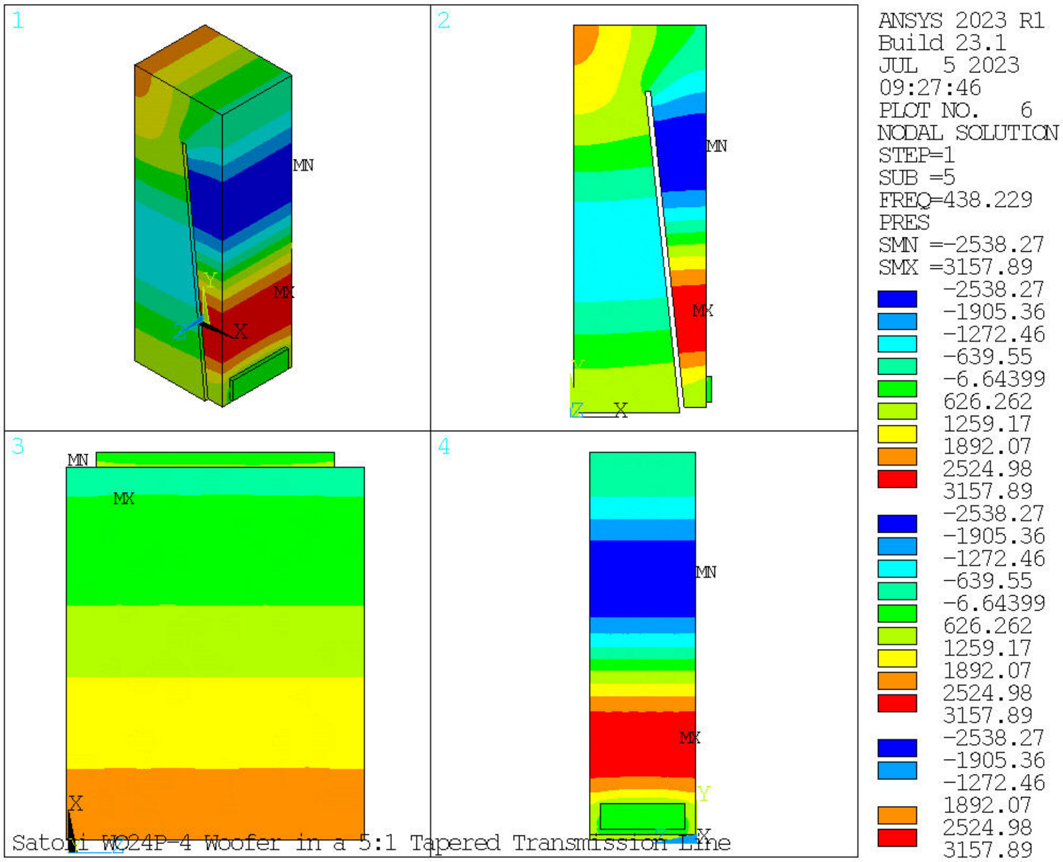
Three quarter wavelength mode at 144.5 Hz.



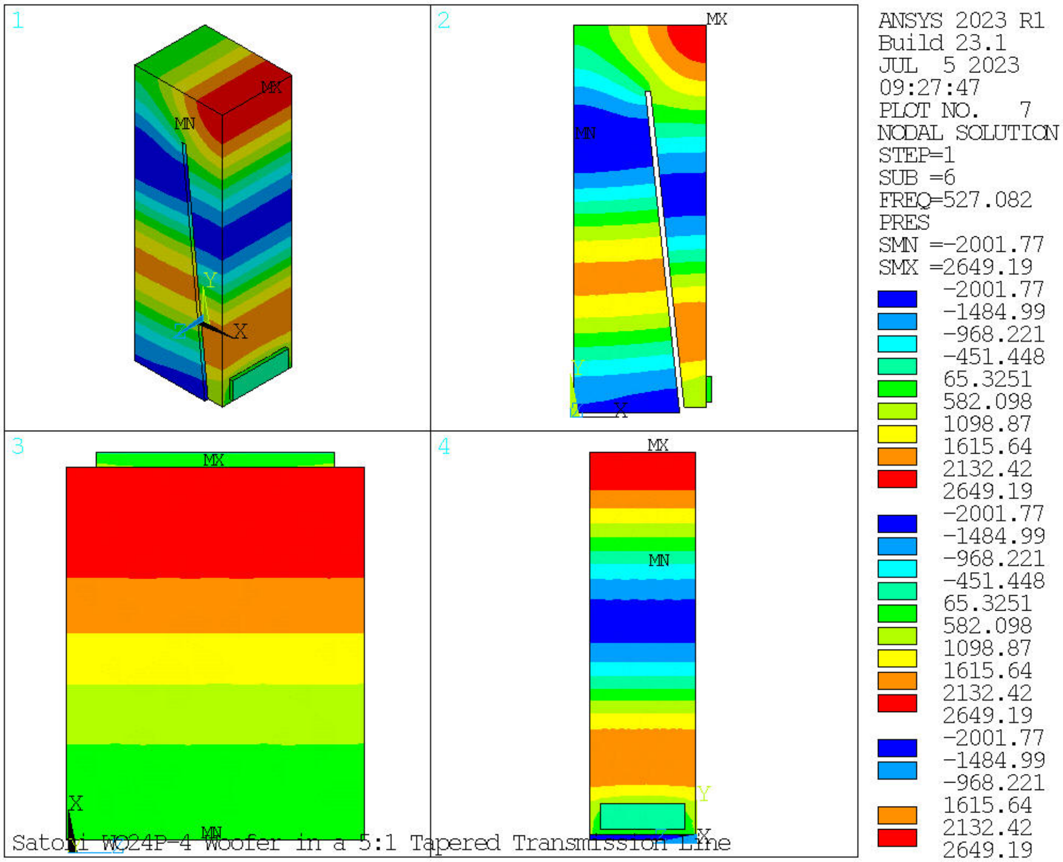
Five quarter wavelength mode at 242.8 Hz.



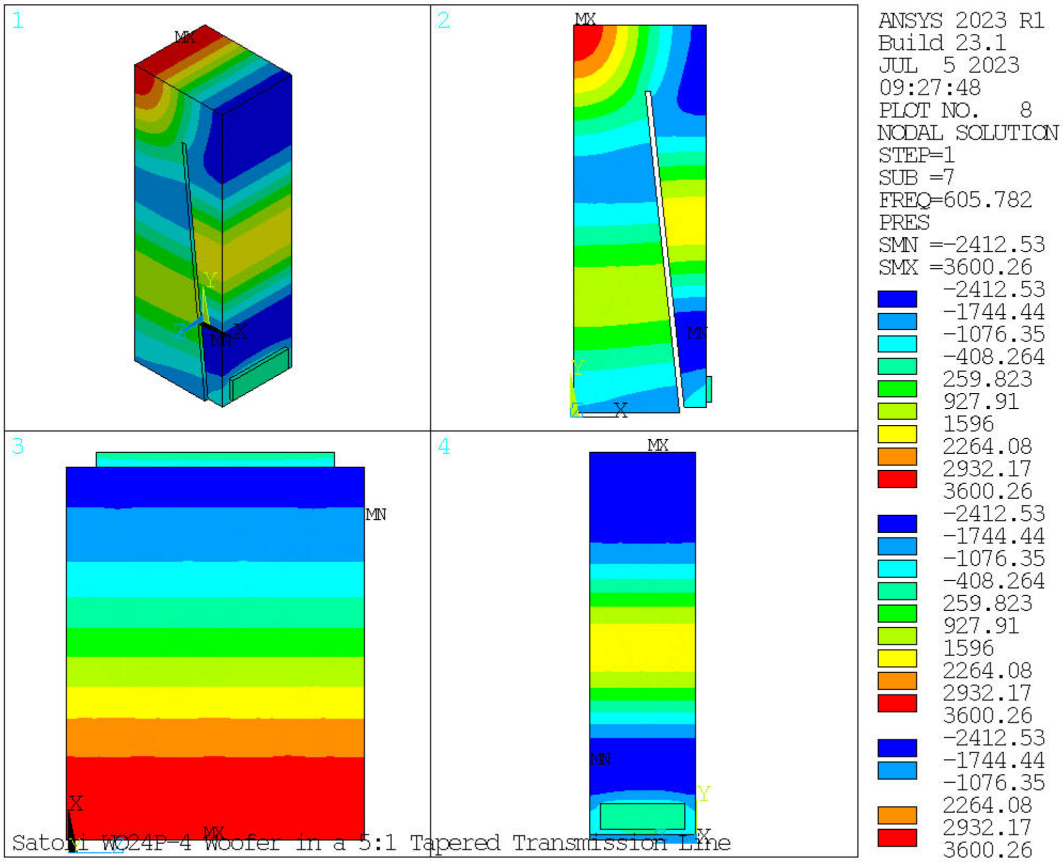
Seven quarter wavelength mode at 339.7 Hz.



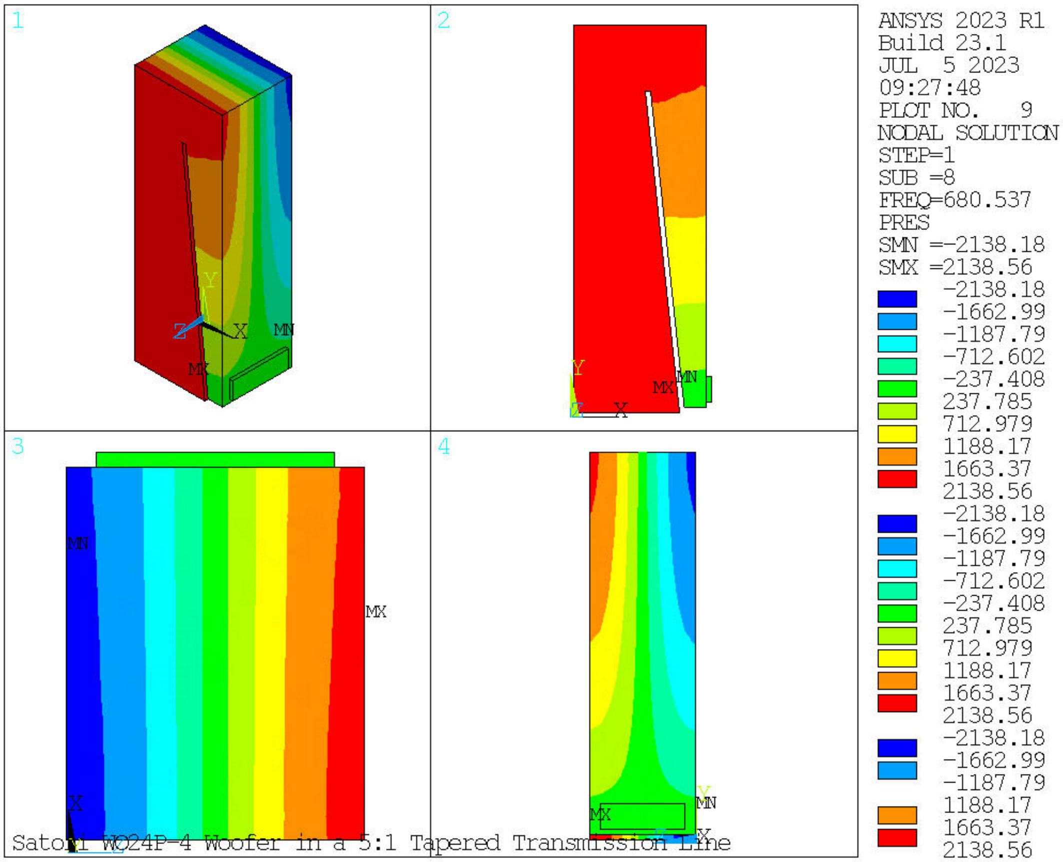
Nine quarter wavelength mode at 438.2 Hz.



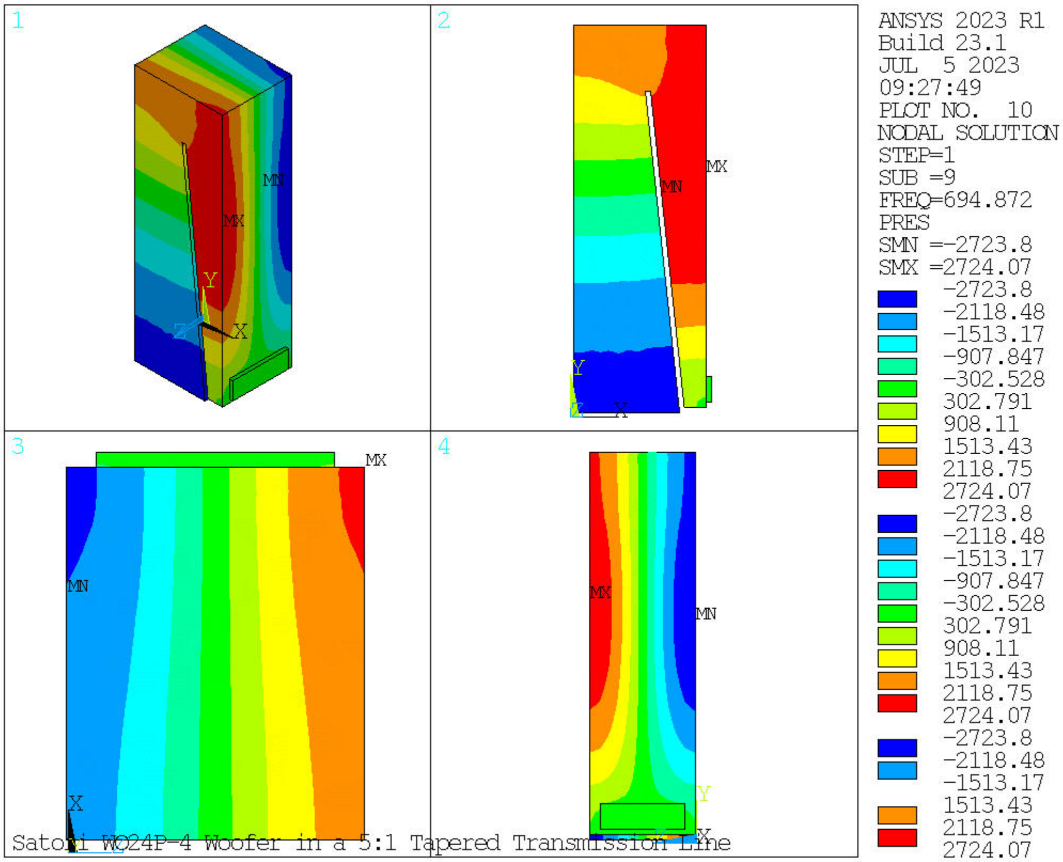
Eleven quarter wavelength mode at 527.1 Hz.



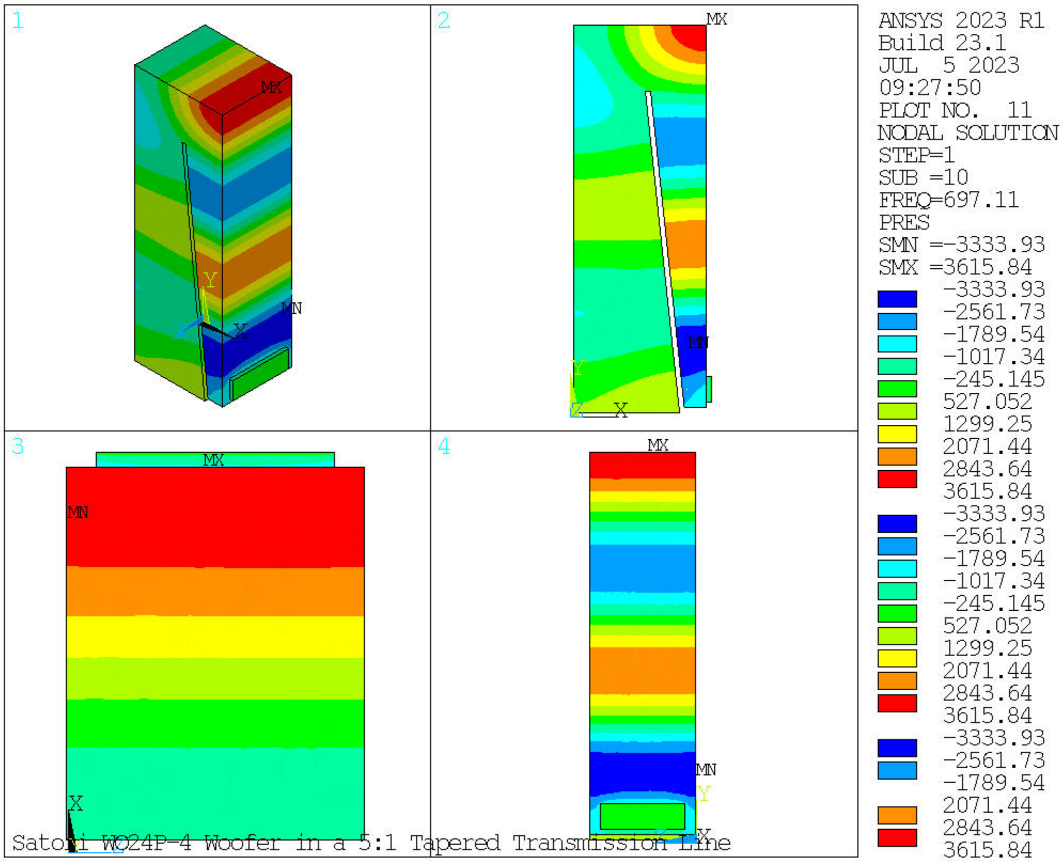
Thirteen quarter wavelength mode at 605.8 Hz.



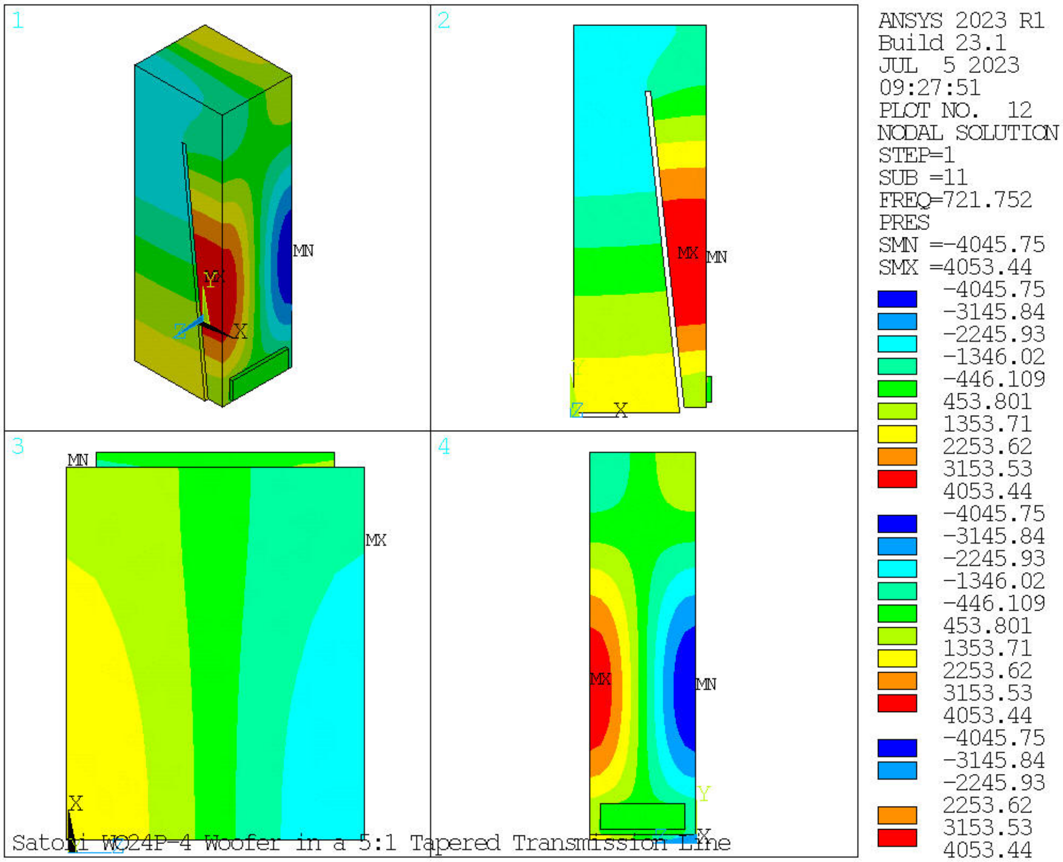
First non-axial mode at 680.5 Hz.



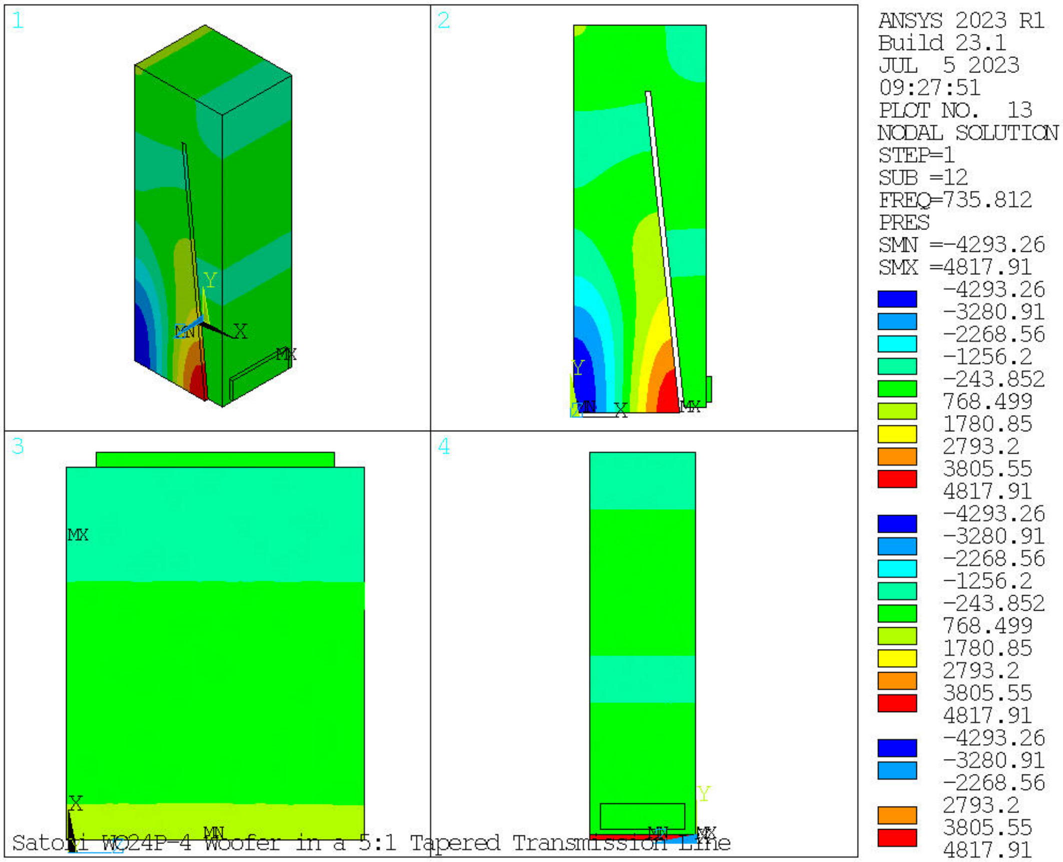
Second non-axial mode at 694.9 Hz.



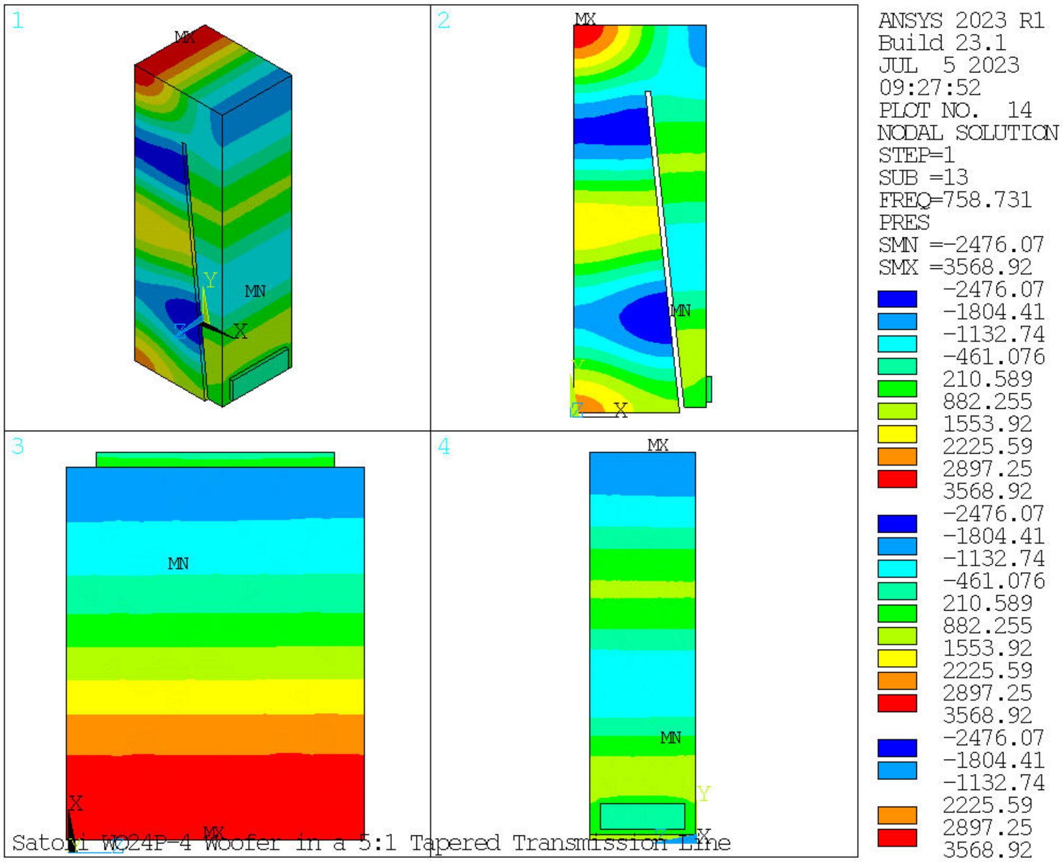
Fifteen quarter wavelength mode at 697.1 Hz.



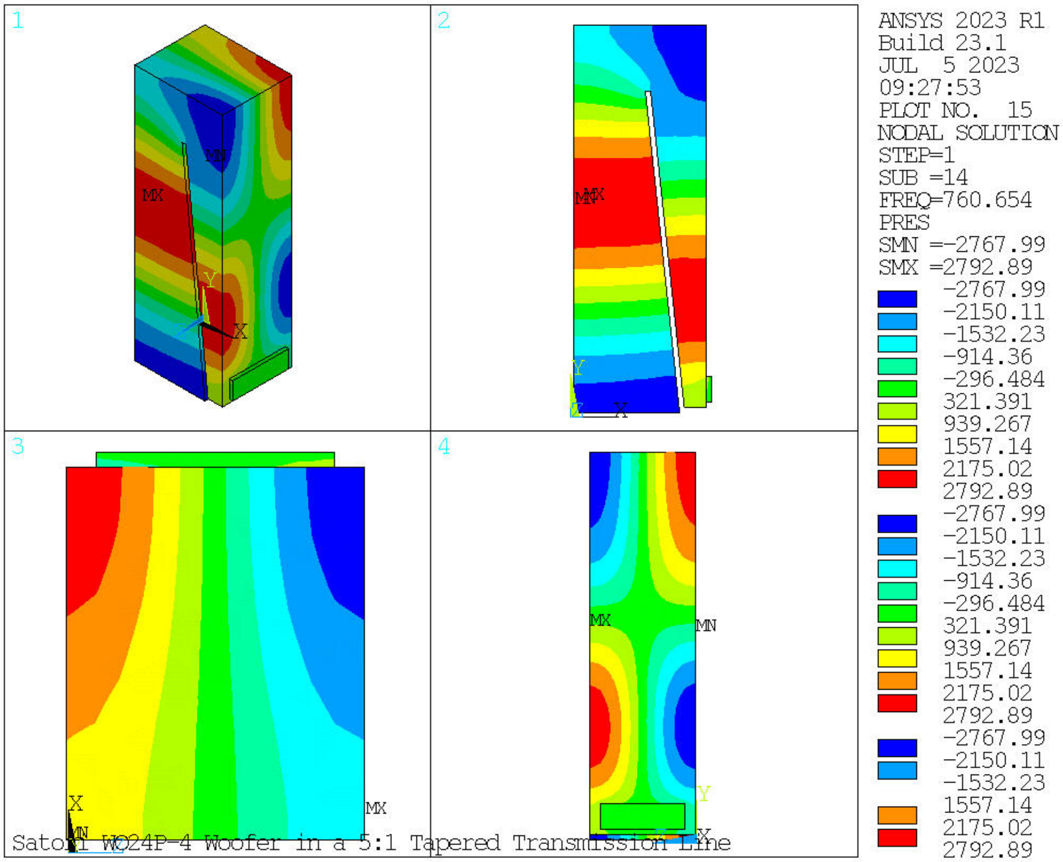
Third non-axial mode at 721.8 Hz.



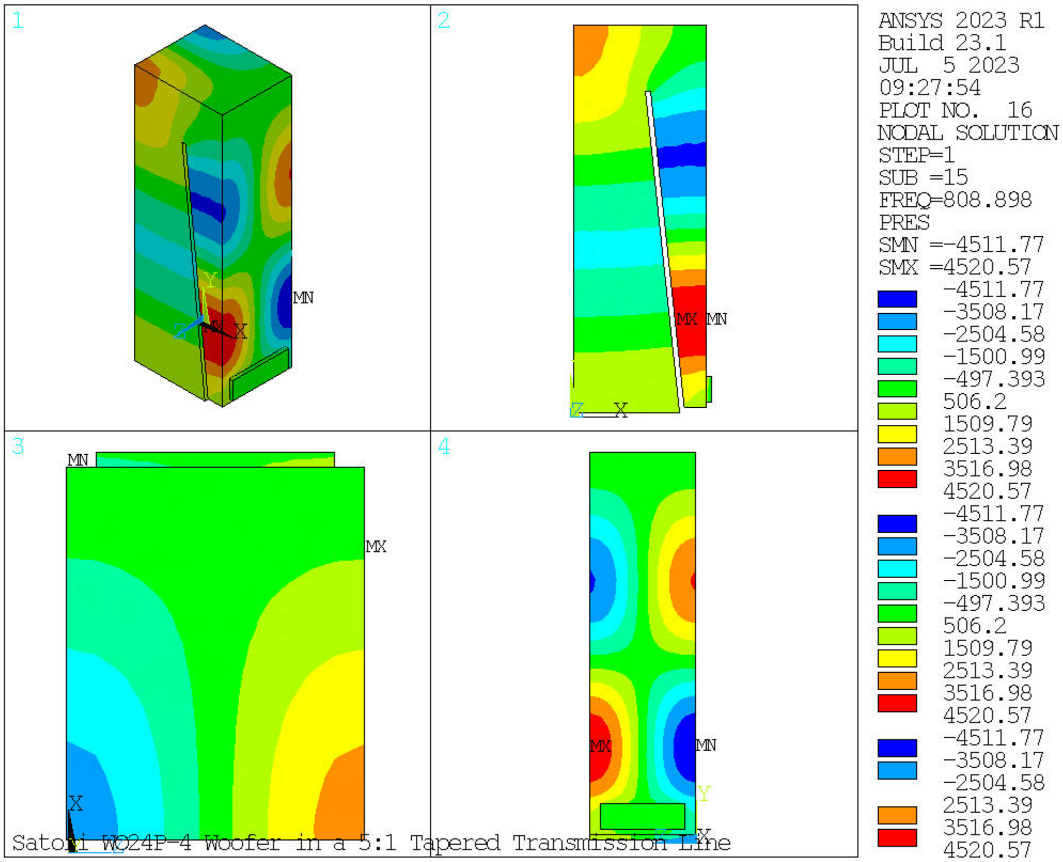
Fourth non-axial mode at 735.8 Hz.



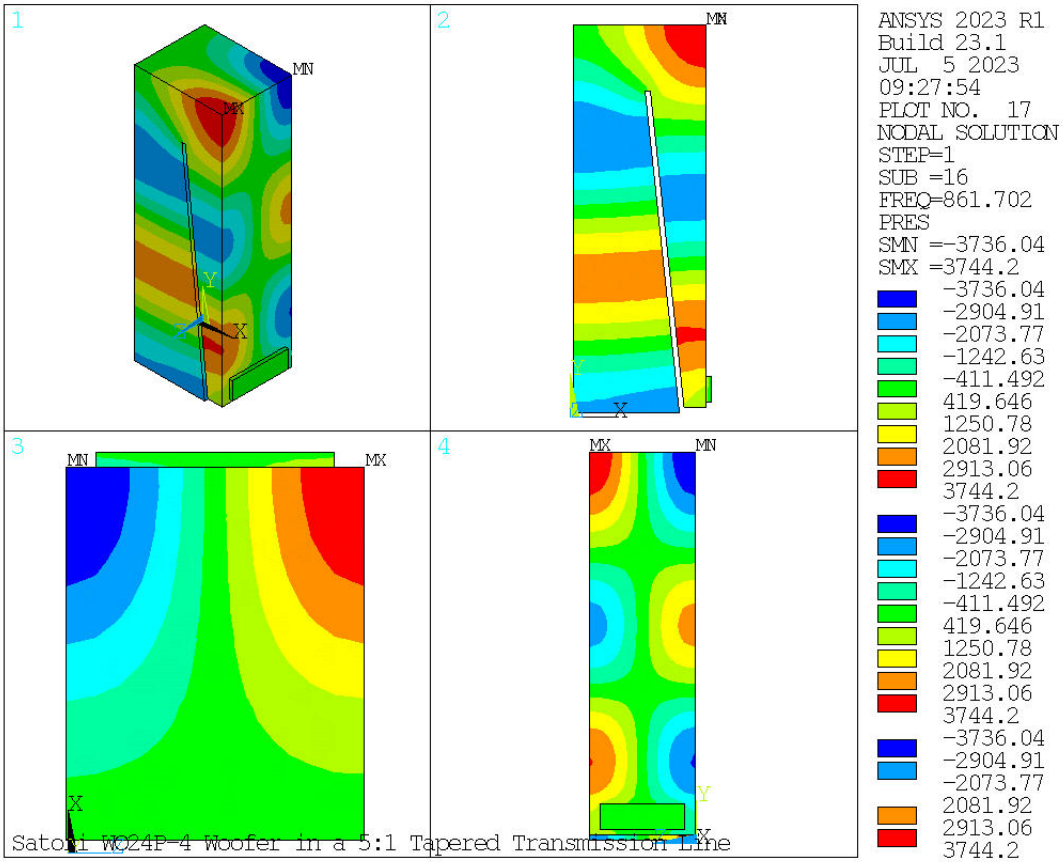
Higher axial mode at 758.7 Hz.



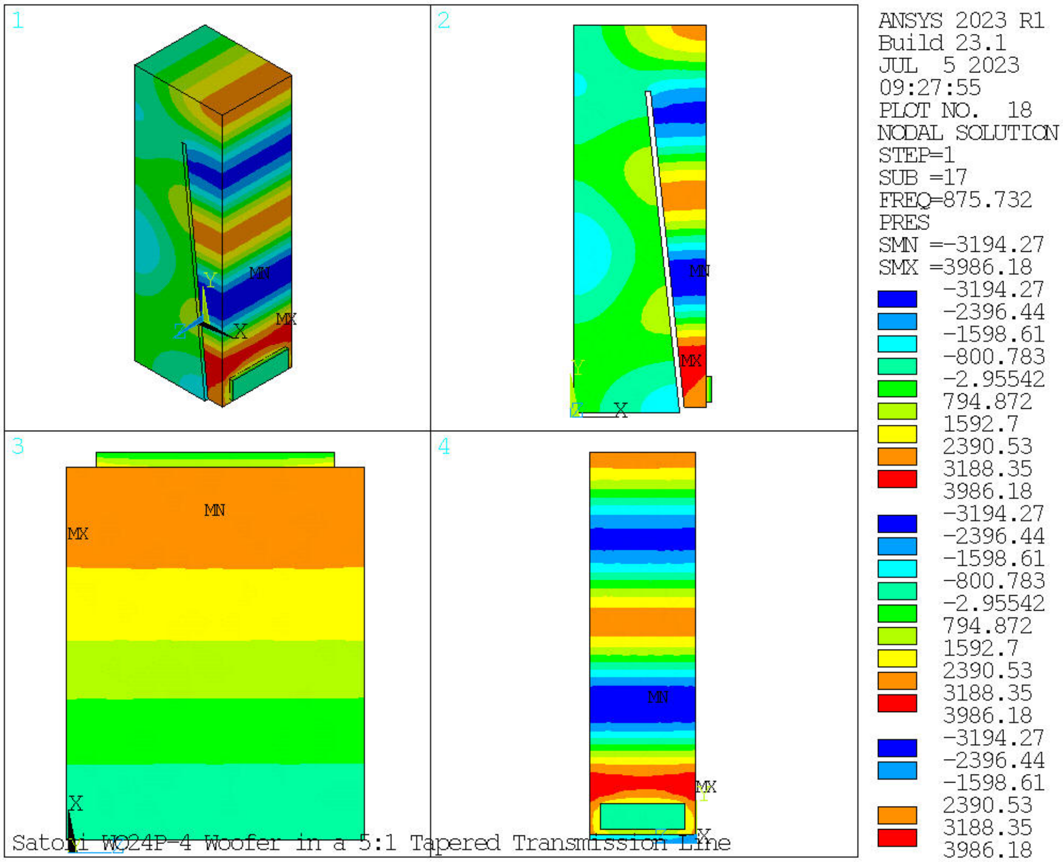
Fifth non-axial mode at 760.7 Hz.



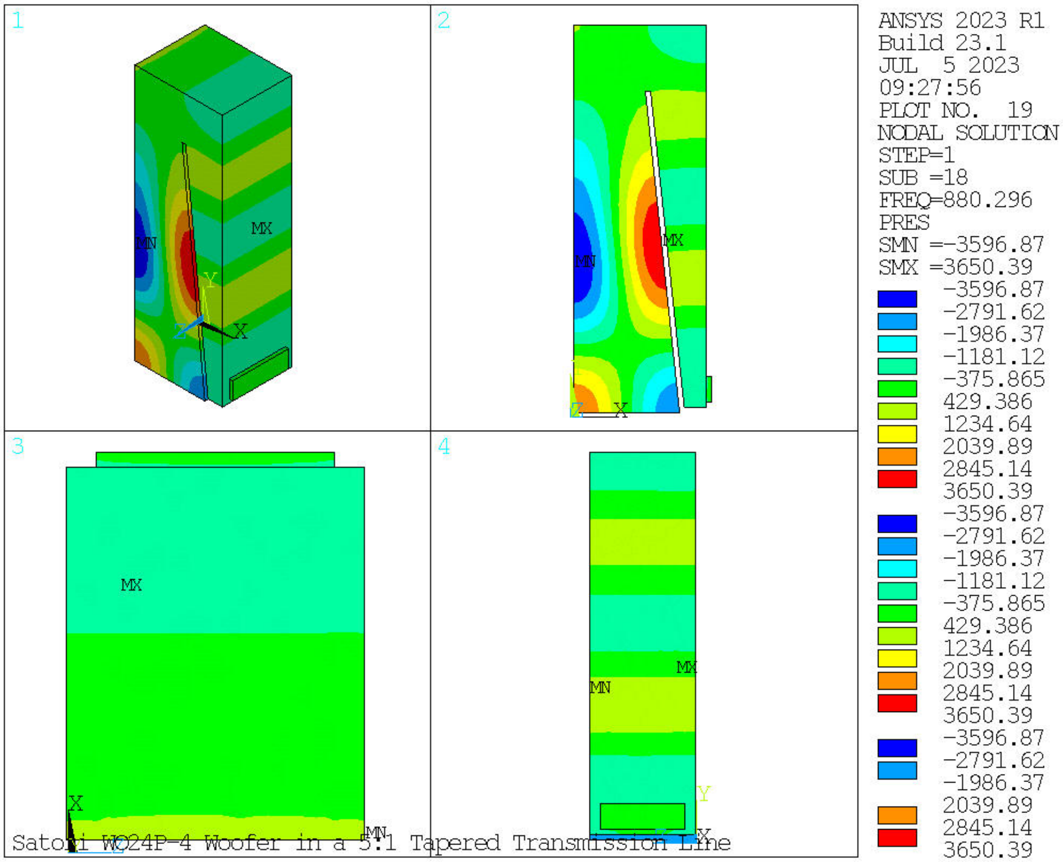
Sixth non-axial mode at 808.9 Hz.



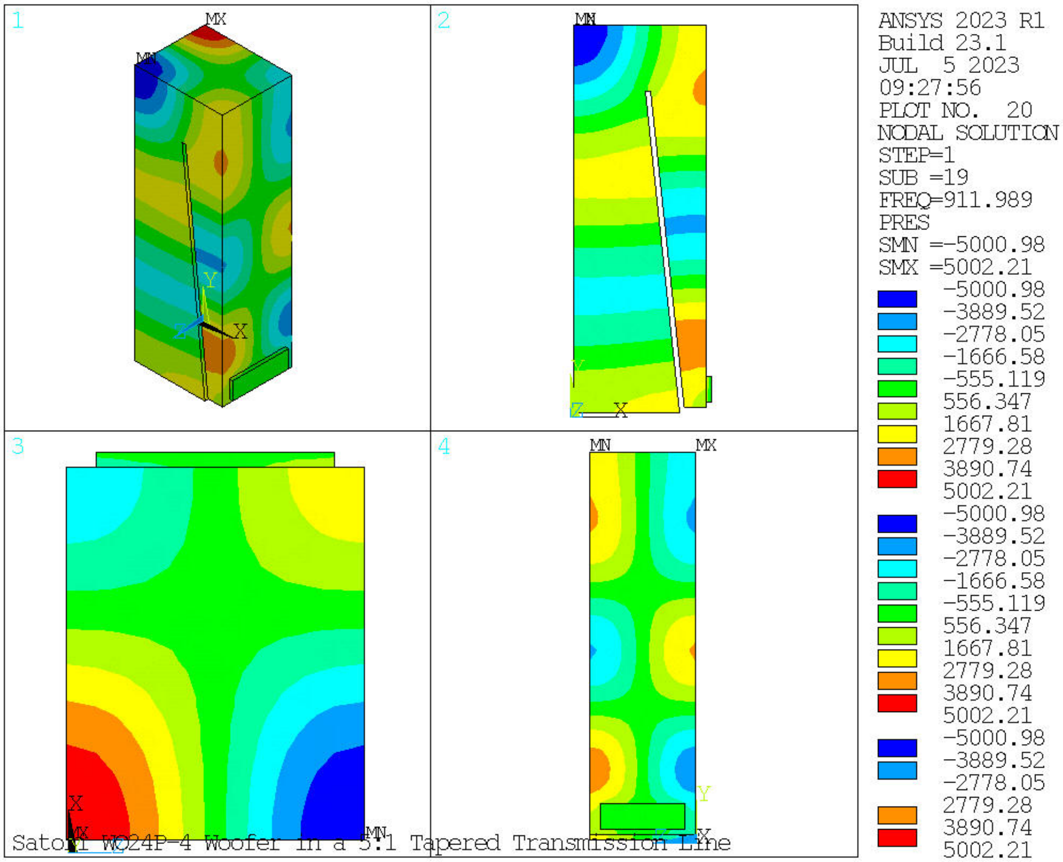
Seventh non-axial mode at 861.7 Hz.



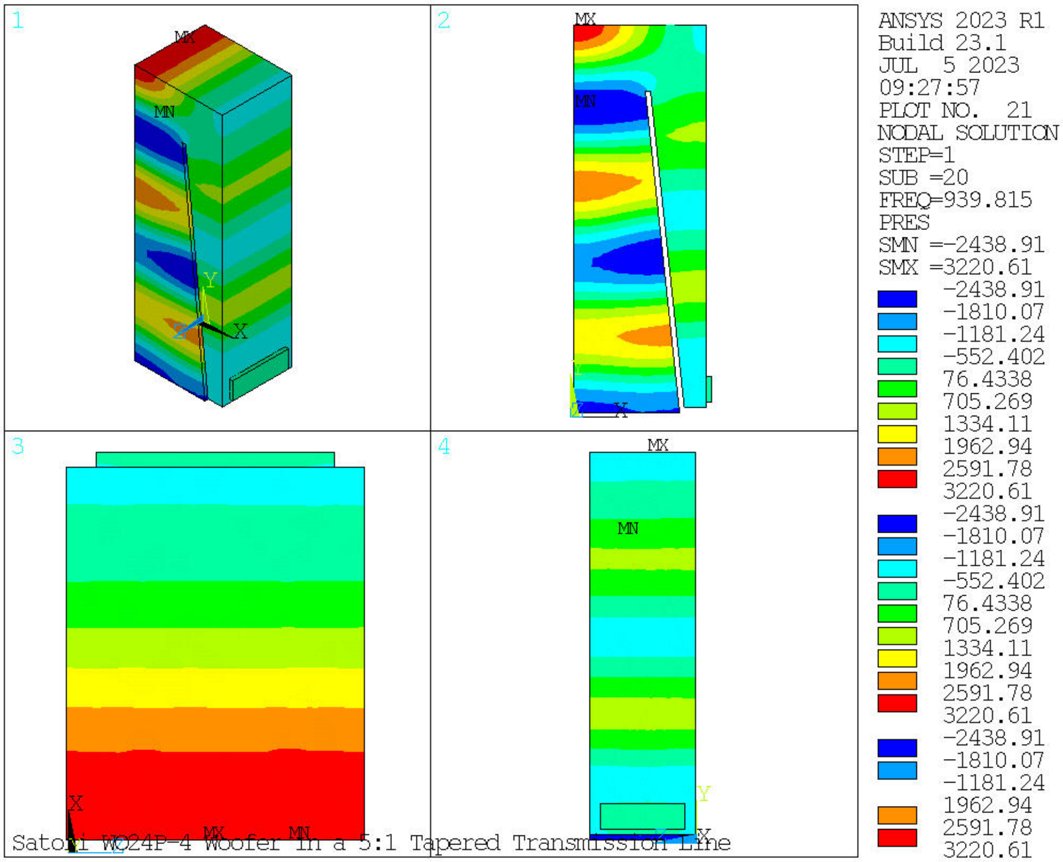
Higher axial mode at 875.7.



Eighth non-axial mode at 880.3 Hz.



Ninth non-axial mode at 912.0 Hz.

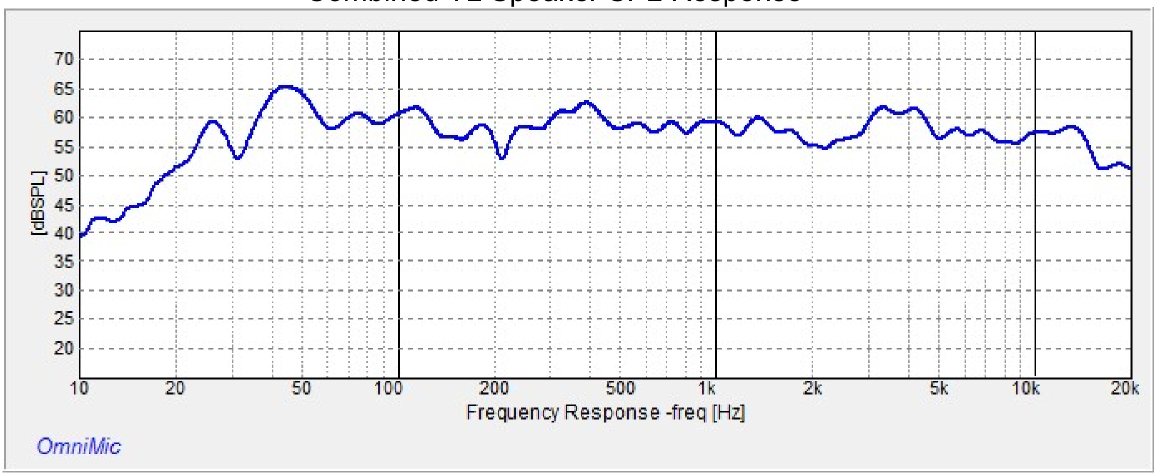


Higher axial mode at 939.8 Hz.

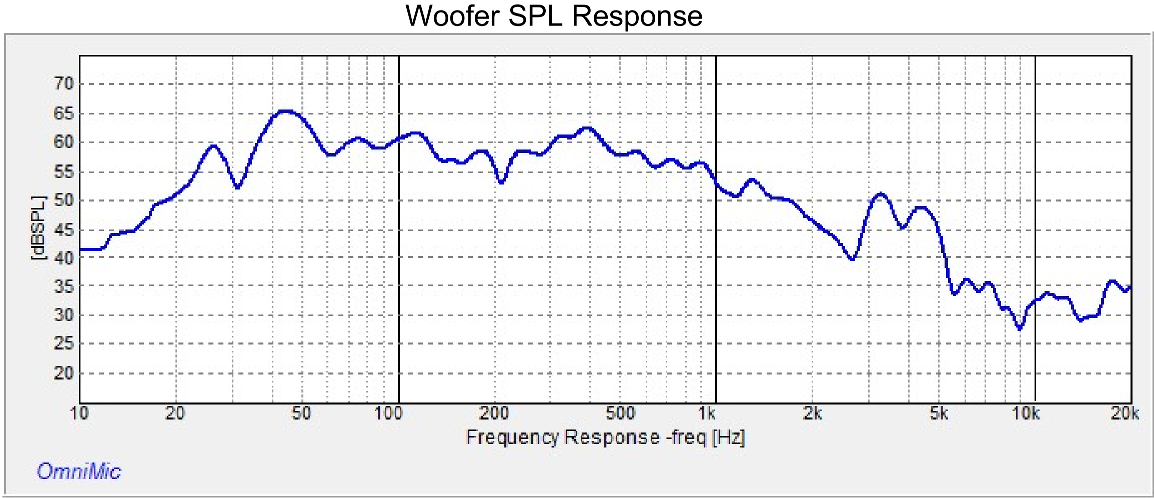
Attachment 4 : Raw Omnimic SPL Measurement Results (1/12 Octave Smoothing)

- Left Speaker Active Crossover

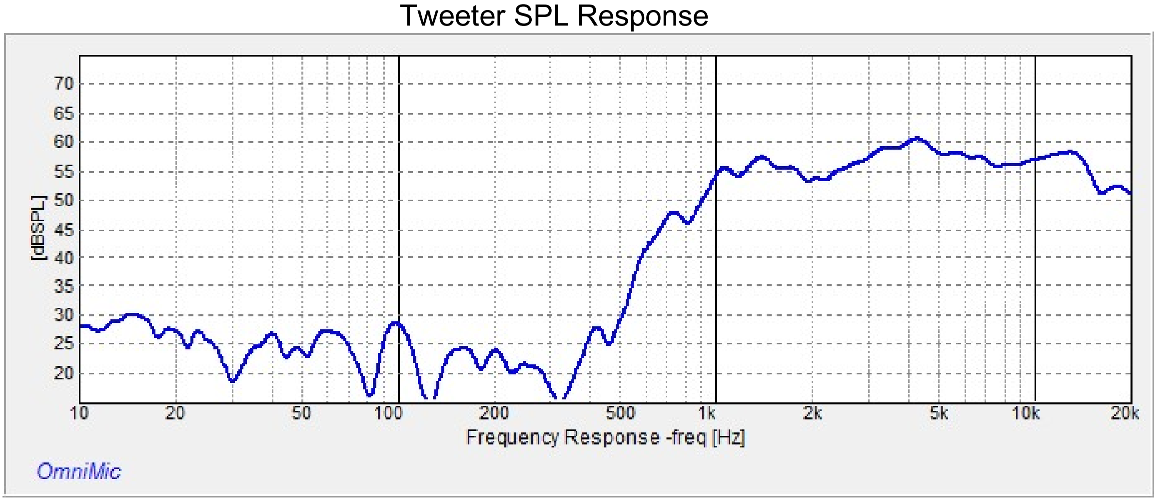
Combined TL Speaker SPL Response



Woofer SPL Response

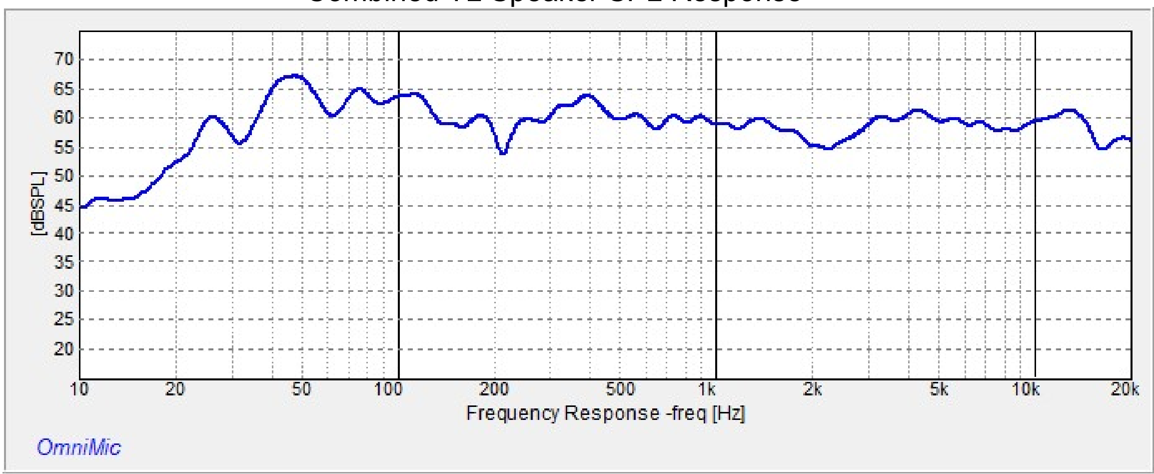


Tweeter SPL Response

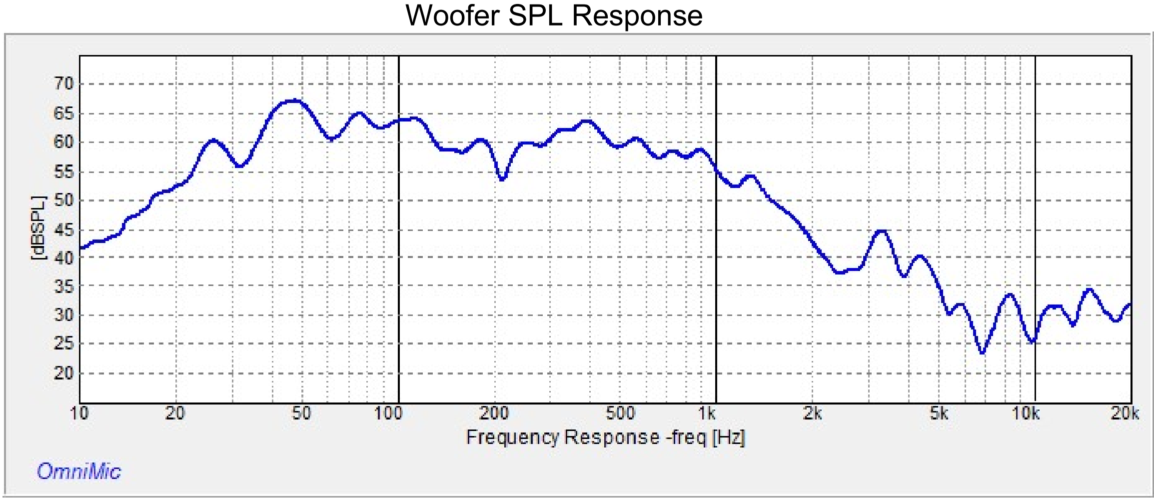


- Left Speaker Passive Crossover

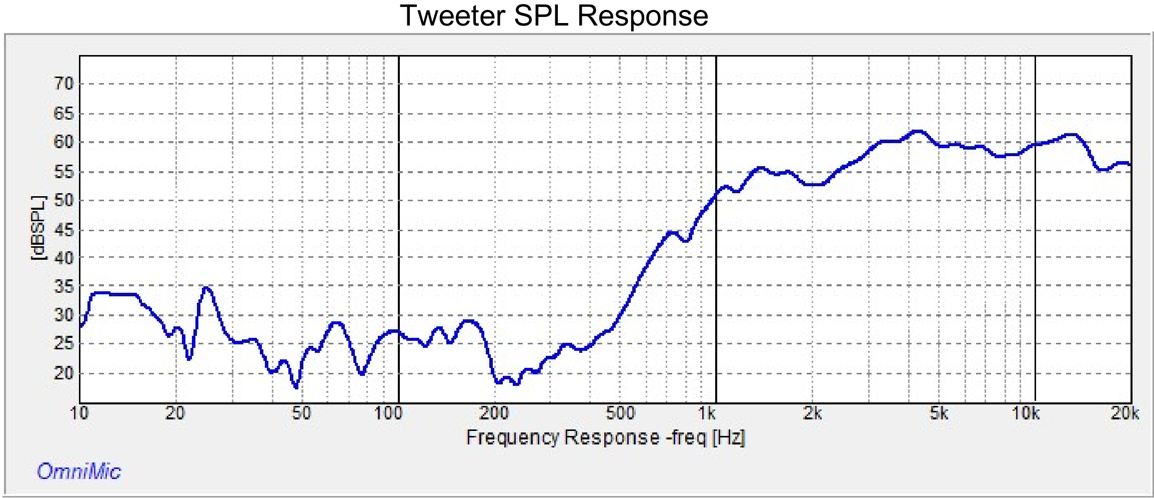
Combined TL Speaker SPL Response



Woofer SPL Response

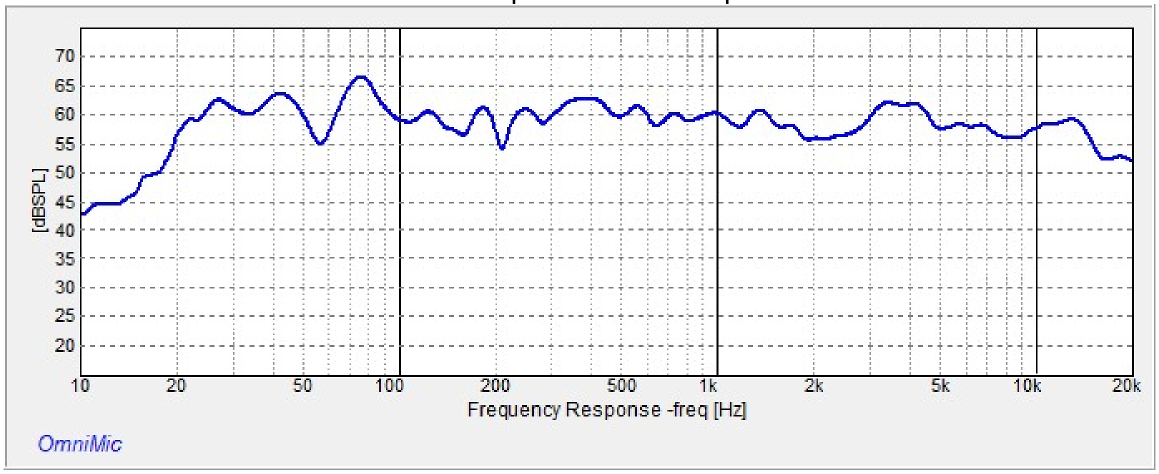


Tweeter SPL Response

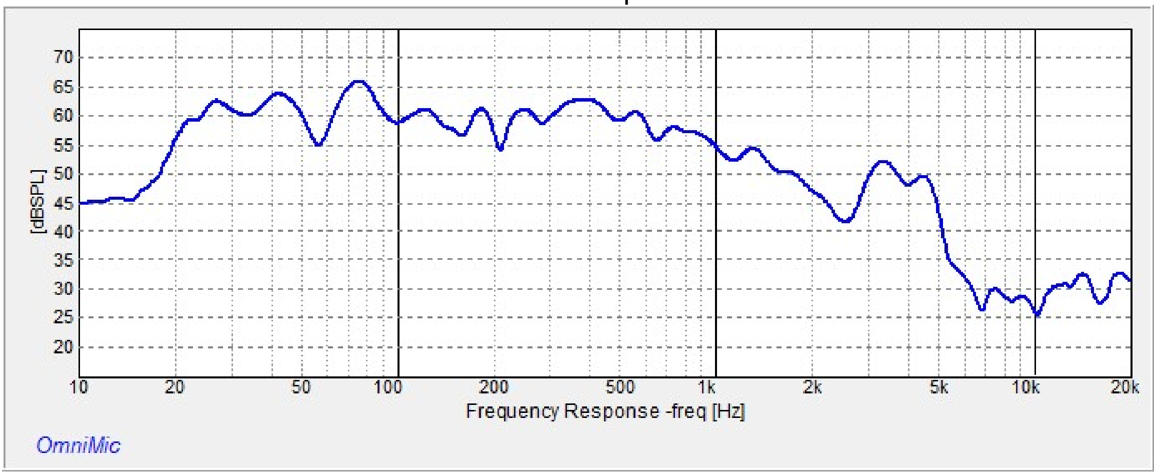


- Right Speaker Active Crossover

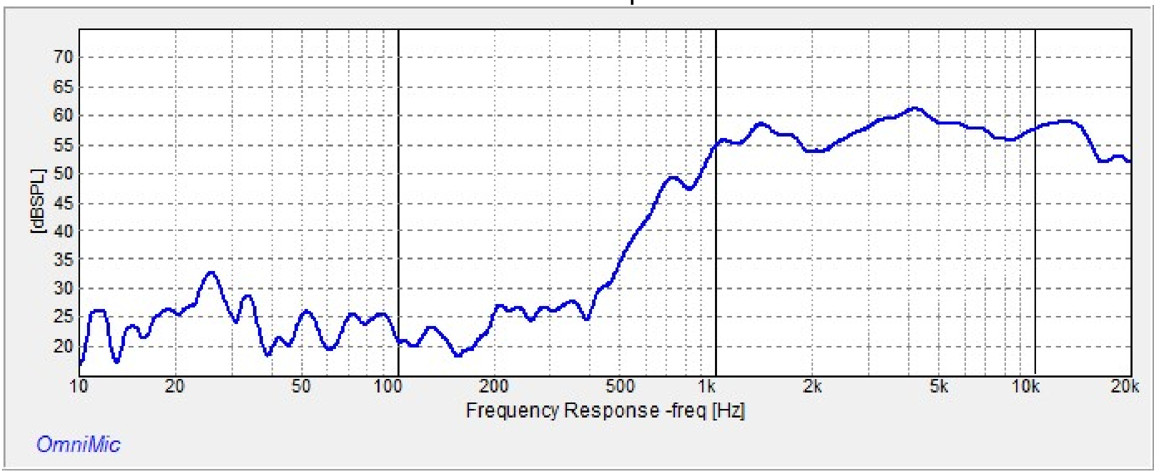
Combined TL Speaker SPL Response



Woofer SPL Response

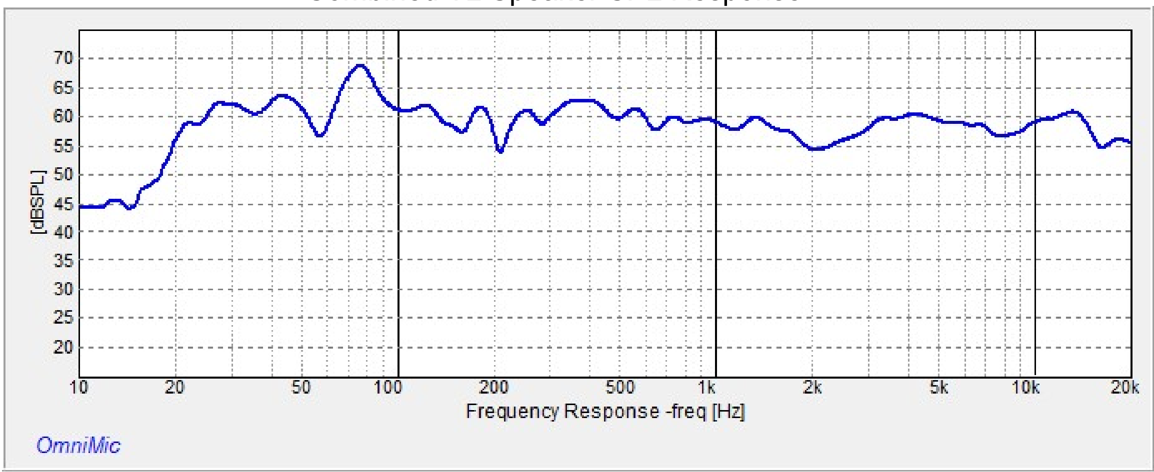


Tweeter SPL Response

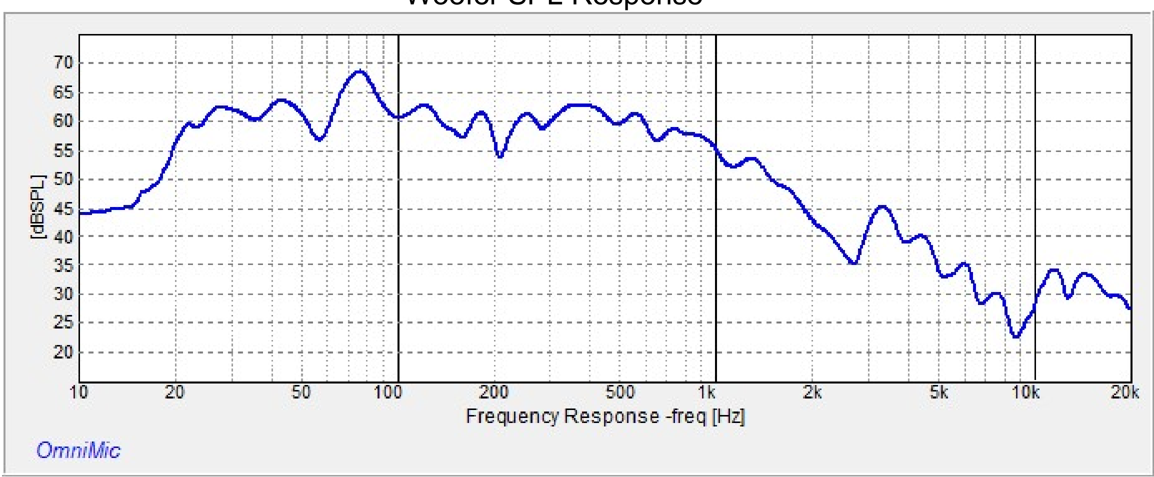


- Right Speaker Passive Crossover

Combined TL Speaker SPL Response



Woofer SPL Response



Tweeter SPL Response