Using Modal Analysis to Understand Transmission Line Speaker Enclosure Response Part 2 – Measurements and Analyses

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Introduction

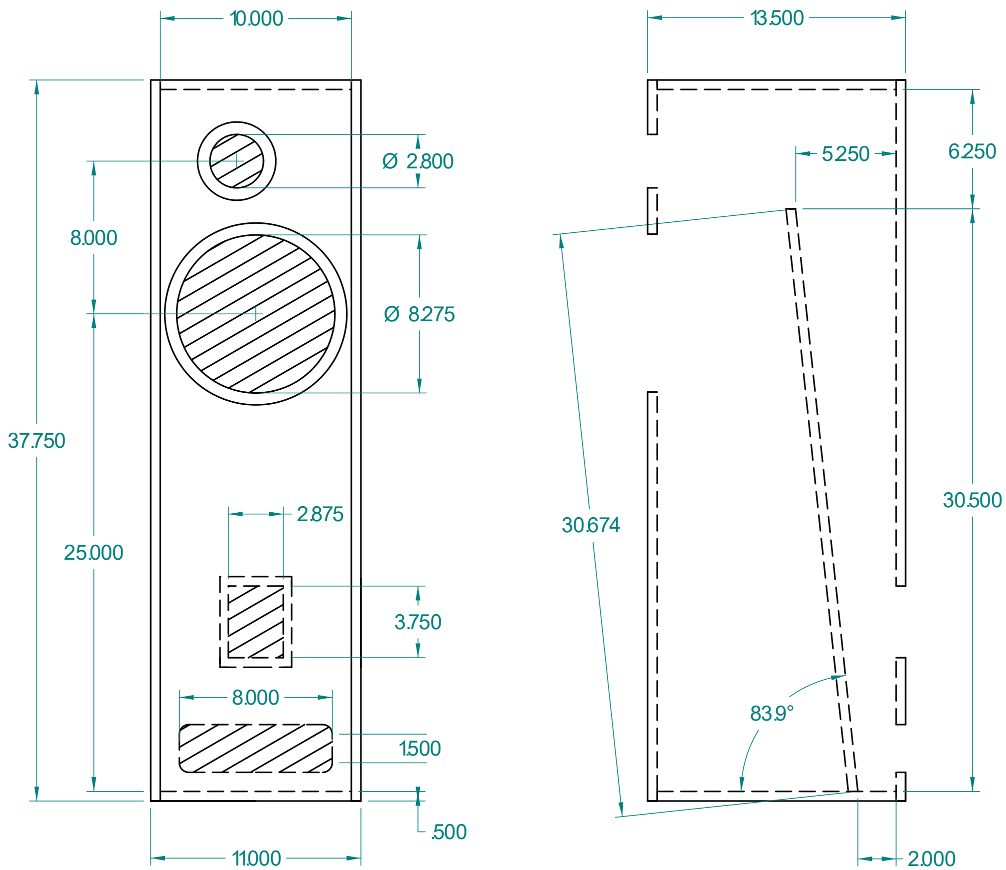
In Part 1, the concepts of modal analysis were introduced. In structural vibration analyses, knowing the resonant frequencies and associated mode shapes a mechanical system's response to an arbitrary excitation can be predicted. The vibrating portion of a loudspeaker, particularly a distributed mass/stiffness acoustic enclosure like a transmission line, can be considered a mechanical system and modal methods used to understand its behavior and performance.

An arbitrary excitation will excite all modes to various degrees depending on the frequency content and the location of excitation. The summation of the individual modal responses will yield the complete system response. If an excitation is focused at a single frequency, or a narrow band of frequencies, the nearby modes in the frequency domain will dominate the summed system response. Also, depending on the location of excitation modes may be strongly excited or not at all. The intent of this presentation is to study the modes calculated from a set of mathematical models and use these results to interpret and understand the measured near field SPL response of a TL loudspeaker.

The Satori TL Speaker Design

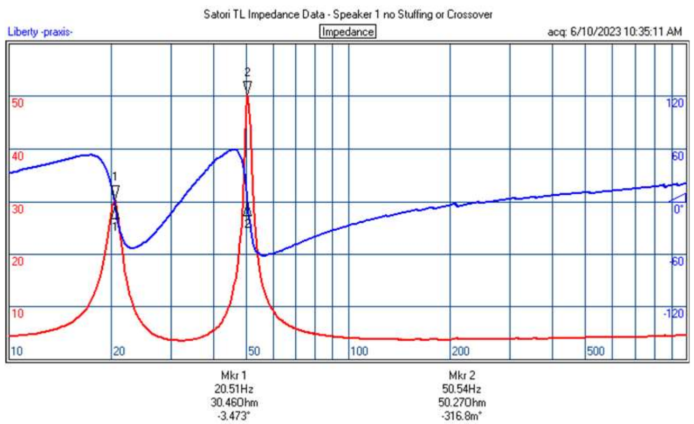
My recently completed Satori TL will be used as a test bed for several upcoming presentations. During the original design and build, a complete set of nearfield and in room SPL acoustic measurements as well as electrical impedance measurements were made. The initial write-up contained some of these measurements and correlation with simulation results. Selected measurements taken during the build and verification of the TL design will be examined in more detail in this study.

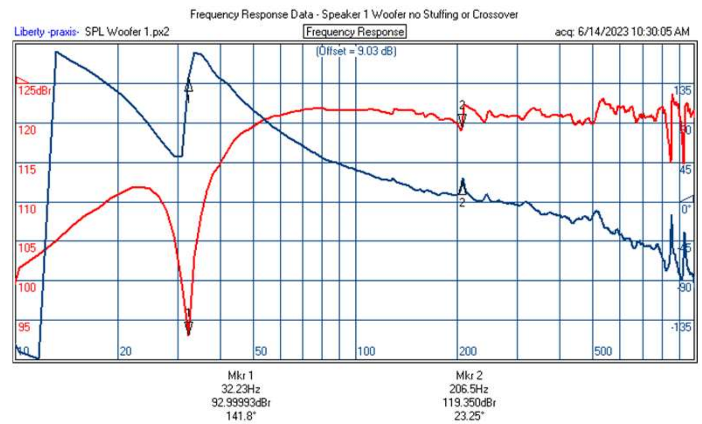
http://www.quarter-wave.com/Project13/Project13.html

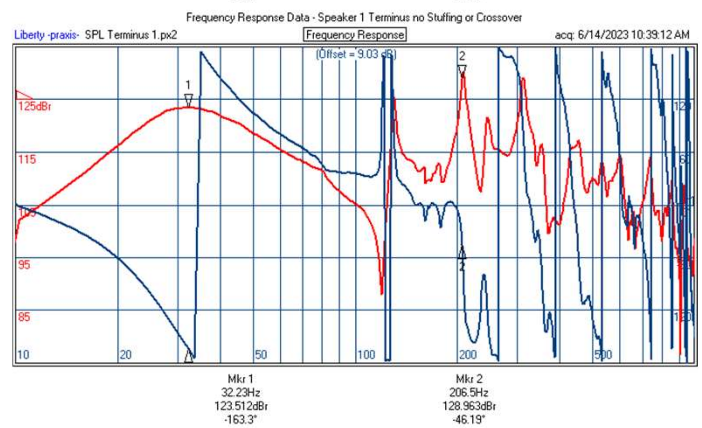


Sketch of the 5:1 tapered Satori transmission line speaker enclosure. All dimensions are in inches.

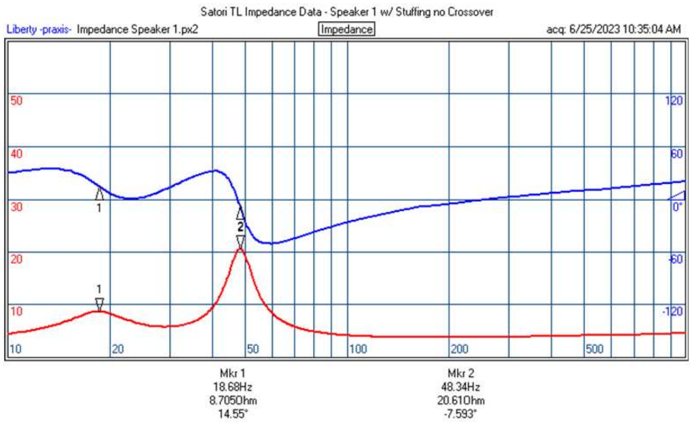
Raw Near Field Measurements

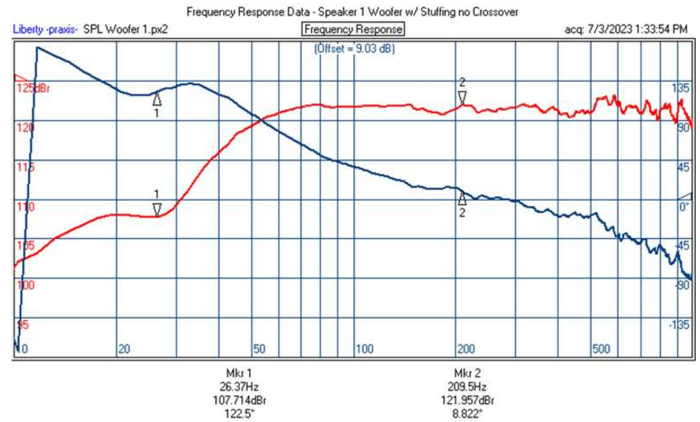




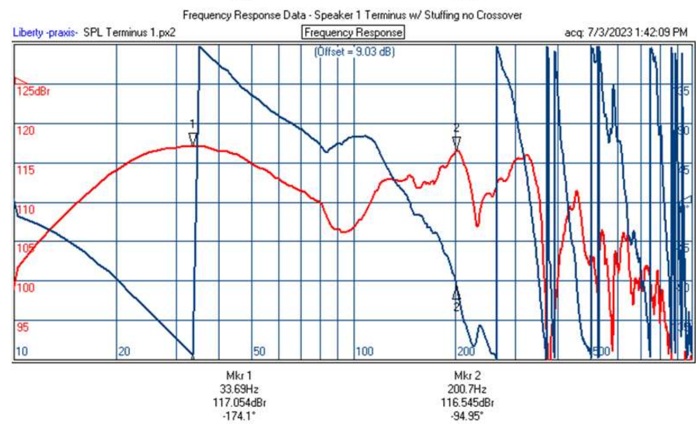


Impedance and near field measurements of the empty left TL speaker are shown, the right TL speaker results are almost the same. Top left plot shows electrical impedance, top right plot is the woofer SPL, and bottom right plot is the terminus SPL. Near field SPL measurements were taken centered 0.25 inches off the driver dust cap and rear baffle plane at the terminus.



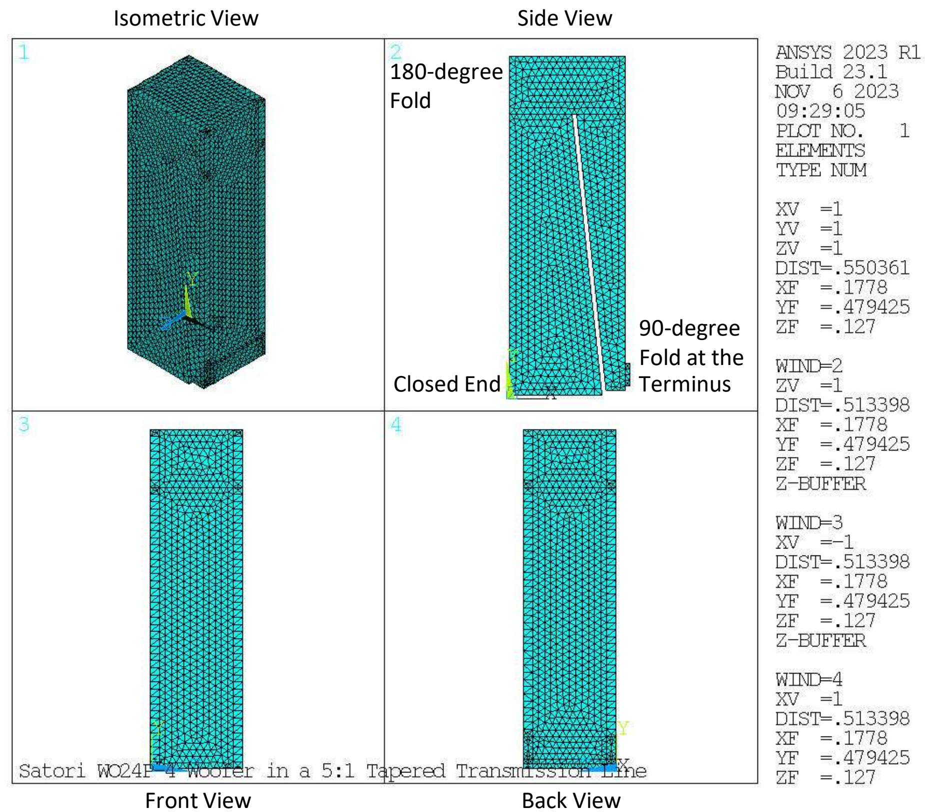


Impedance and near field measurements of the stuffed left TL speaker, the right TL speaker results are almost the same. Top left plot shows electrical impedance, top right plot is woofer SPL, and bottom right plot is terminus SPL. Near field SPL measurements were taken centered 0.25 inches off the driver dust cap and rear baffle plane at the terminus.



Models Used in the Analyses

Two linear models were used to study the resonant frequencies and mode shapes in the Satori TL enclosure. Below is a 1D MathCad model of the geometry, it was used during the design phase to calculate the resonant frequencies, mode shapes, as well as the loudspeaker impedance and SPL responses. At right is a 3D ANSYS FEM model used to calculate the resonant frequencies and mode shapes for just the air volume.



The 1D MathCad model can be solved quickly and efficiently. It assumes the oscillating pressure and velocity are constant for cross-sectional areas normal to the centerline. The model treats the enclosure geometry as if it were a straight line with local expansions and contractions representing changes in cross-sectional area at the corners or the restriction at the terminus. The boundary condition at the terminus can be either a simple zero pressure and zero velocity slope or a frequency dependent acoustic impedance. This 1D model was used to represent the enclosure subsystem to calculate resonant frequencies and mode shapes of the air volume in the TL as well as the complete speaker system (woofer plus air volume) to calculate the electrical impedance and SPL responses.

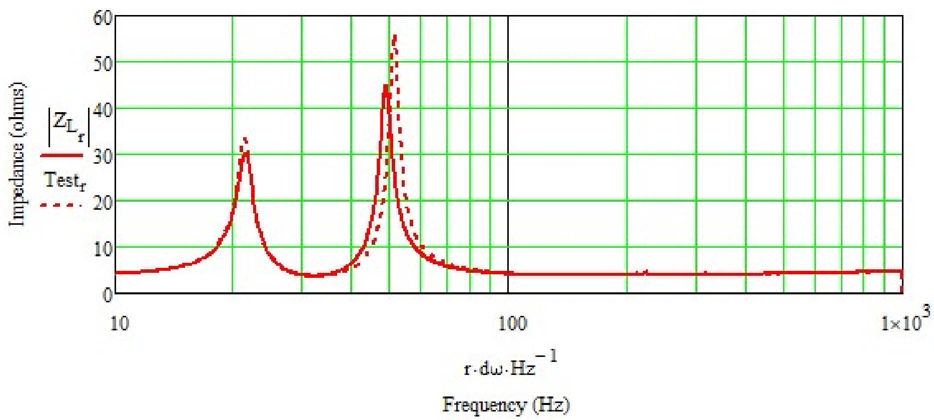
The 3D ANSYS FEM takes longer to solve and only calculates the resonant frequencies and mode shapes of the air volume in the enclosure subsystem. There are no assumptions made on the oscillating profiles along the length for the pressure distribution in the enclosure. The boundary condition at the terminus is set to zero pressure. Contour plots of the pressure profile/distribution for each mode shape are insightful for understanding the oscillating air velocity behavior along the TL's length including through the folds.

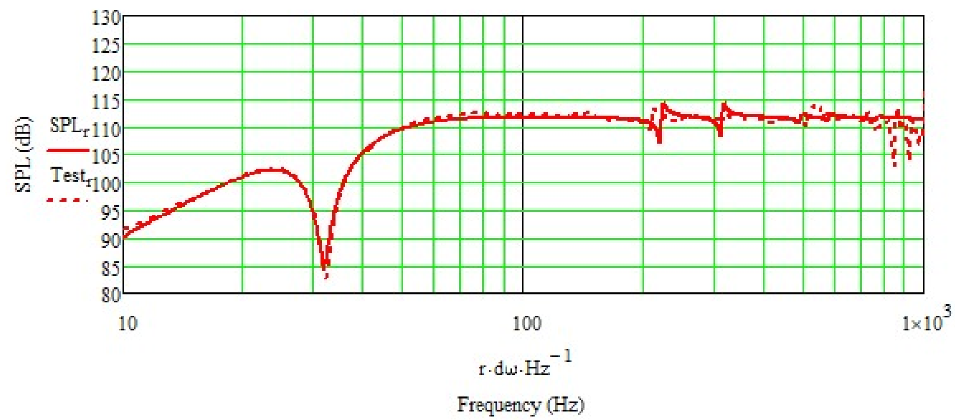
Correlating results of both models with test data needs to be done carefully to ensure an apples-to-apples comparison and to keep track of the impact of the assumptions on each model's results. The air volume displaced by the back of the driver, particularly the large magnet, is not considered in either analytical model.

Correlation of Measurements and Analyses

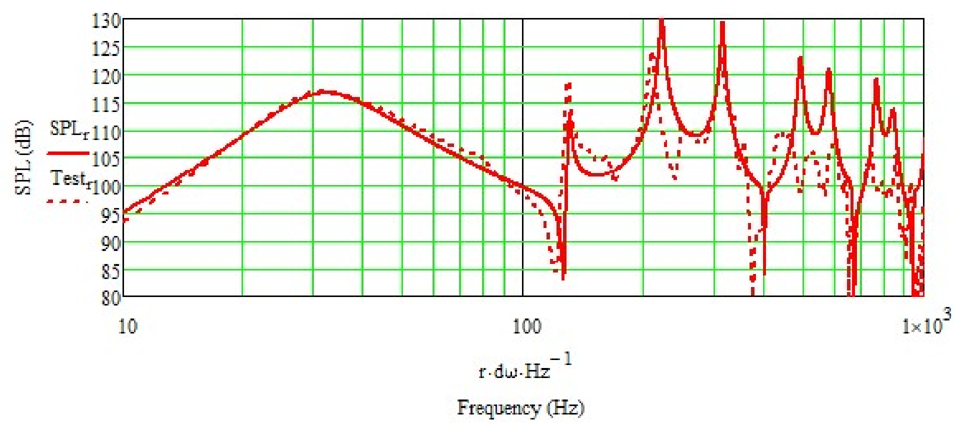
The design of the Satori TL was done entirely with the latest MathCad models. As part of the verification process, small signal electrical impedance and near field SPL measurements were performed using Praxis to determine how accurate the simulations predicted the measured responses. The raw measurement data shown on previous slides was exported from Praxis as text files, imported into the MathCad models, and plotted overlayed on the predictions for the frequency range 10 to 1000 Hz. The electrical impedance and near field woofer SPL measurements and calculated results correlated very well. The near field terminus SPL measurements and calculated results for the empty TL correlated well below 400 Hz but above 400 Hz the correlation was not as clean. The following slides will attempt to shed some light on the air behavior in the empty TL enclosure that led to the differences between measurements and the MathCad predictions for the near field terminus SPL results.

Correlation of the Electrical Impedance and the Near Field Woofer and Terminus SPL Plots

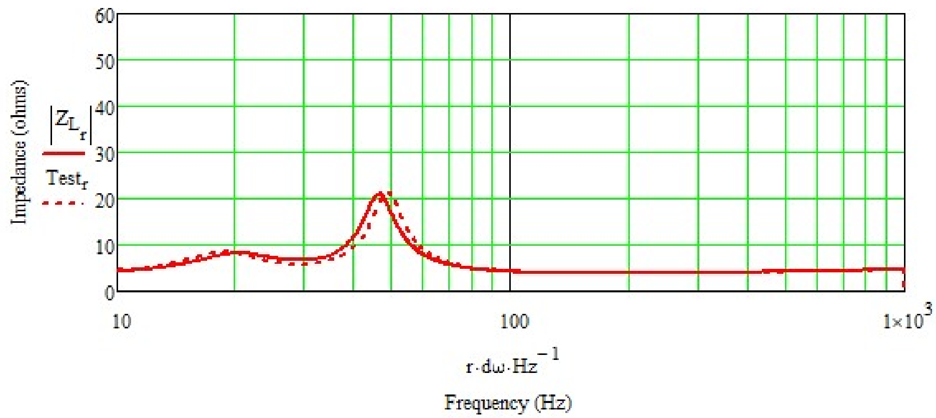


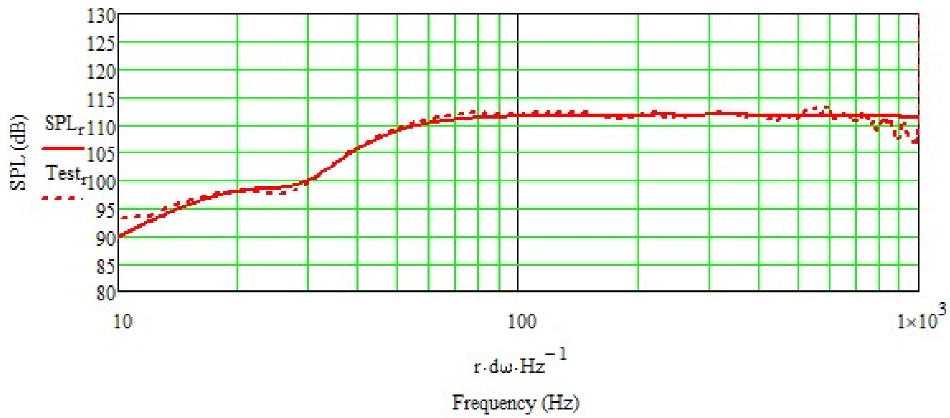


Correlations are shown for the MathCad model and Praxis measurements of the empty right TL speaker. Top left plot shows the electrical impedance, top right plot is the woofer SPL, and bottom right plot is the terminus SPL. The electrical impedance and near field woofer measurements correlate very well. The near field terminus measurement shows peaks and nulls that correlate well below 400 Hz, but above 400 Hz things do not line up as well and there appears to be more peaks and dips in the measurement

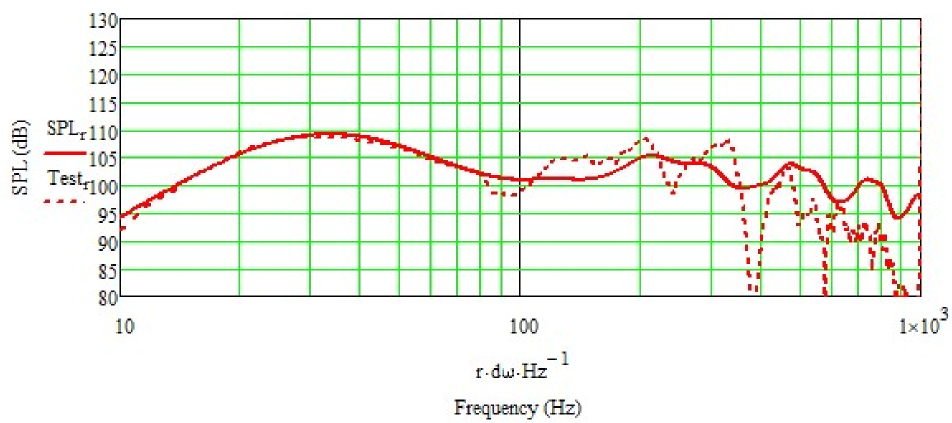


Correlation of the Electrical Impedance and the Near Field Woofer and Terminus SPL Plots

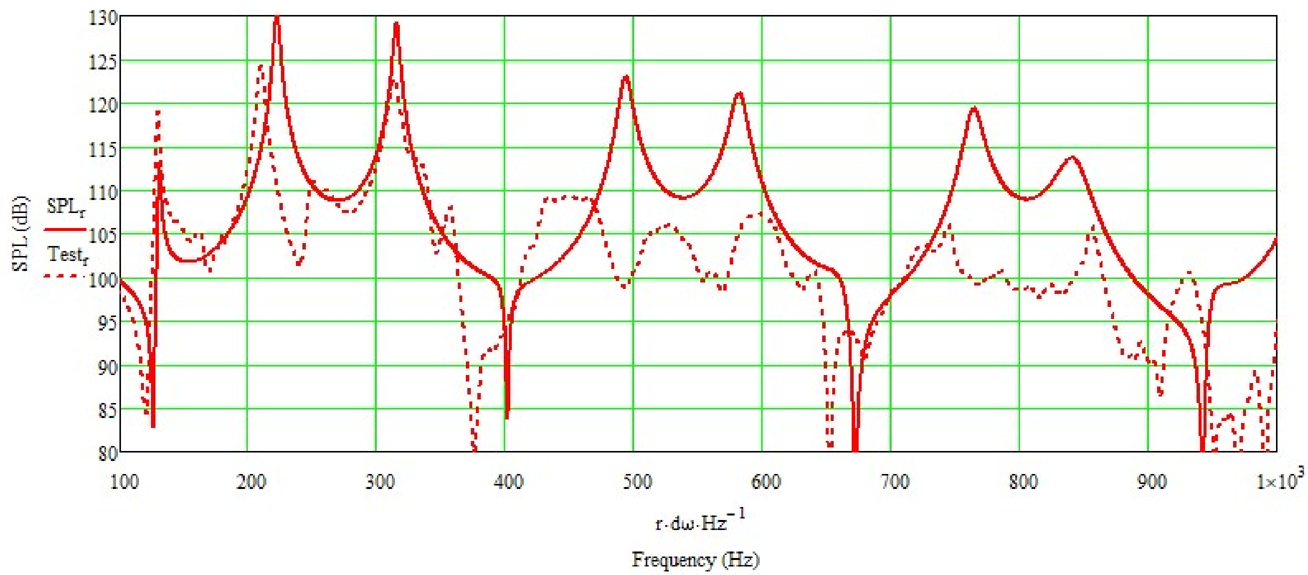




Correlations are shown for the MathCad model and Praxis measurements of the stuffed right TL speaker. Top left plot shows the electrical impedance, top right plot is the woofer SPL, and bottom right plot is the terminus SPL. The electrical impedance and near field woofer measurements correlate very well. The near field terminus prediction and measurement shows rolling peaks and nulls that correlate well below 100 Hz, but above 100 Hz they do not line up and there still appears to be extra peaks and dips in the measurement

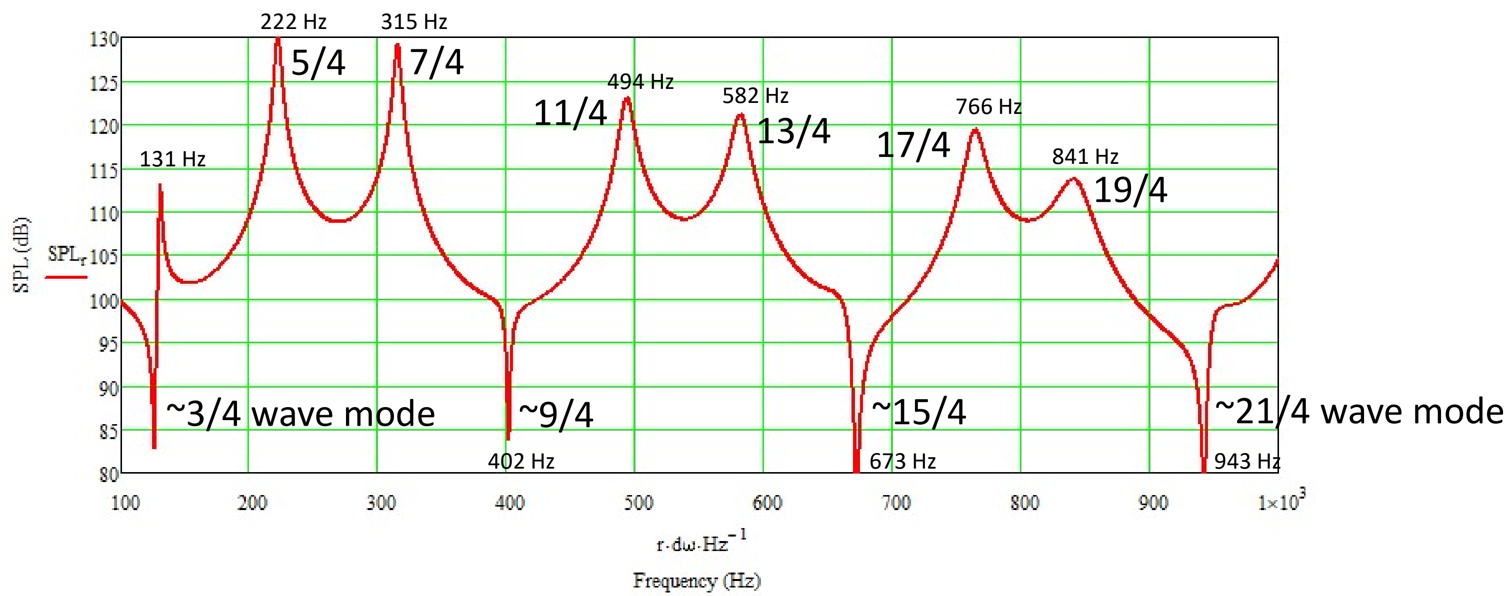


Terminus Calculated and Measured SPL Response for the Empty Transmission Line



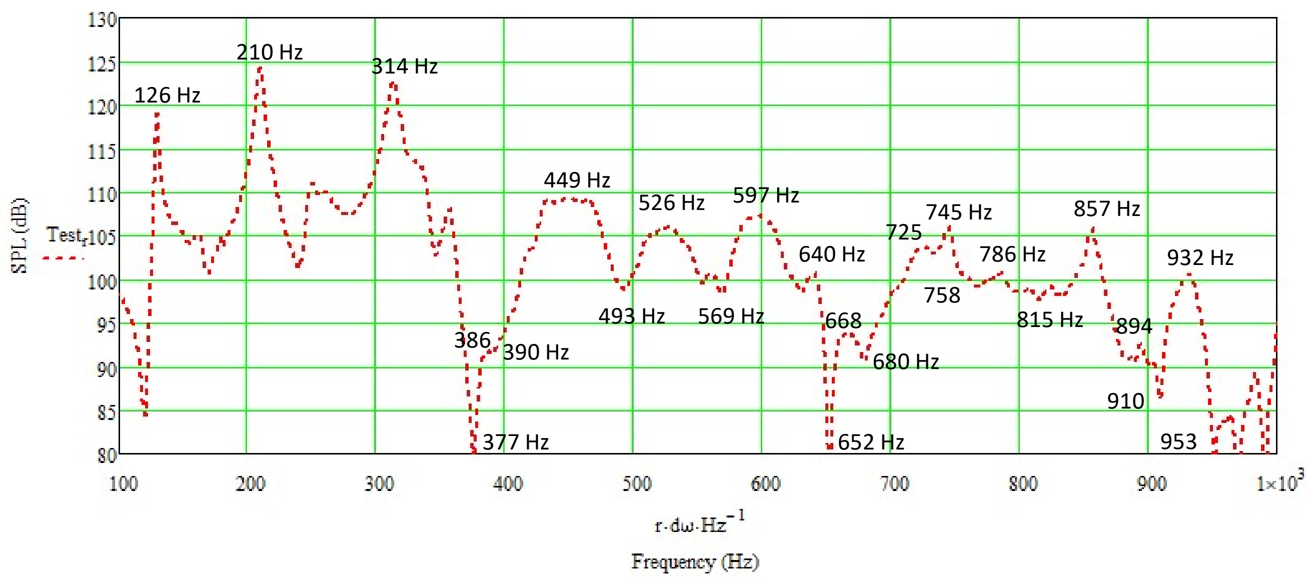
The key to understanding the behavior of the TL enclosure is the undamped terminus SPL plot between 100 Hz and 1000 Hz. The 1D MathCad model results are shown above as the solid red line while the Praxis measured results are shown as the dashed red line. The peaks and nulls result from the standing waves at the respective resonant frequencies. Below 400 Hz, the MathCad model and the measurements correlate well. Above 400 Hz the measured SPL curve exhibits more peaks and dips and is also about 10 dB lower than the calculated curve. Studying these terminus SPL response curves will lead to a better understanding of the air's vibration behavior in the TL enclosure.

Terminus Calculated SPL Response for the Empty Transmission Line



The plot above shows the calculated speaker system terminus response from the 1D MathCad model. The model includes the interaction of the driver on the enclosure resonances and standing waves. The model also includes an acoustic impedance boundary condition at the terminus which at low frequencies acts like an additional mass (effectively extending the length of the TL, the often-referenced end correction).

Terminus Measured SPL Response for the Empty Transmission Line



The plot above shows just the measured terminus SPL response. As much as we work with and believe in simulations, they are only approximations. The plot above displays reality. Compared to the 1D calculated response there are significantly more peaks and nulls, in particularly above 400 Hz, which is evidence of unaccounted for resonances. Some of the peaks and nulls can and will be explained, and some are still an open question requiring additional work if they are to be resolve.

To gain an understanding of the various peaks and dips in the measured near field terminus SPL response, two analytical models were exercised and correlated with the test data.

1. Results from an ANSYS 3D Finite Element Model are shown in Attachment 1. The model calculates the resonant frequencies and mode shapes of the air volume inside the TL enclosure, the natural vibrating motions at the different resonant frequencies. The plots only show the oscillating pressure profile, remember that the velocity profile is a function of the gradient of this pressure profile. The limitation in this model is that the mode shapes are normalized, they tell us the frequency and pressure profile but not the actual pressure magnitude. These frequencies and mode shapes were correlated and tabulated with the peaks and dips in the measured terminus SPL data.

2. Results from a MathCad 1D model were used to calculate the air's oscillating volume velocity, pressure, and displacement magnitudes for each of the various axial mode's peaks and dips in the terminus SPL response, they are shown in Attachment 2. The limitation in this model is the missing influences of the non axial resonances in the calculated results (the extra peaks and nulls in the measurement data).

After reviewing these two sets of comparisons, several observations will be offered. Not often are the internal air motions and pressures plotted for a speaker enclosure. Many of the statements made about internal air behavior in a TL speaker enclosure are just speculations that get repeated enough times they take on some degree of validity. Some of these theories are really good and insightful observations, while some are just plain old BS.

Mode	MathCad	ANSYS 3D	Description
Tuning --->	34	35	1/4 Wavelength
3	134	144	3/4 Wavelength
4	228	242	5/4 Wavelength
5	321	339	7/4 Wavelength
6	415	437	9/4 Wavelength
7	506	526	11/4 Wavelength
8	597	605	13/4 Wavelength
		680	1/4 Side to Side
		694	3/4 Side to Side
9	691	695	15/4 Wavelength
		721	5/4 Side to Side
		735	1/4 Front to Back
10	778	757	17/4 Wavelength
		759	7/4 Side to Side
		807	9/4 Side to Side
		860	11/4 Side to Side
11	877	873	19/4 Wavelength
		878	3/4 Front to Back
		910	13/4 Side to Side
12	961	938	21/4 Wavelength
	[Hz}	[Hz}	
Simple BC at the Terminus : p = 0 and du/dt = 0			

The resonant frequencies and mode shapes calculated by the ANSYS 3D finite element model are contained in Attachment 1. For each mode, the pressure contour plot is shown from different views on the left side of the page. On the right side of each page, the pressure profiles along inside (top) and outside (bottom) paths proceeding from the closed to the open end are also plotted. Looking closely at the pressure contour and path plots, remembering that velocity is a function of the pressure gradient, every mode has a component of velocity in the TL path's axial direction. Air vibration at the open end produces the measured near field SPL.

The table at the left summarizes the ANSYS model's calculated resonant frequencies and mode shapes. The ANSYS 3D model results shown in the table assume a simple BC at the terminus, an acoustic end correction is not included. These resonant frequencies should in general be a little higher than the speaker system's calculated and test results.

For comparison, the MathCad 1D subsystem model, just the air volume in the TL, with the same simple BC is also shown in the table. The highlighted rows in the table are all modes with the potential for producing a null in the terminus SPL response due to a minimum axial acoustic impedance between the offset woofer position and the closed end (approximately 3/4, 9/4, 15/4, and 21/4 wavelength axial pressure profiles).

The correlation between the MathCad 1D model and the ANSYS 3D model is good up to the frequency where additional modes are calculated from the 3D geometry. Above 600 Hz, the density of modes in the frequency domain increases significantly because of the 3D solution.

None of the results in the table include the impact of an offset driver, they strictly describe the natural vibration behavior of the air column in the TL enclosure.

Reviewing the frequencies tabulated on the previous slide, and the plotted results shown in Attachment 1, several observations are made.

1. The resonant frequencies and mode shapes are of the TL air volume subsystem only. This is equivalent to the center columns shown in the tables in Part 1 Slide 16.
2. The color contour plots show the pressure profile in the air volume for the various resonant frequencies, these are the mode shapes. The pressure values are oscillating between positive and negative at the resonant frequency of the mode shape, picture the color contours flipping colors (red to blue and back to red at the extremes) during each vibration cycle.
3. The magnitude of the pressure is a normalized value and not an actual magnitude. Good for picturing the behavior and distribution but not very useful in assessing the impact on the driver's cone motion, the enclosure walls, or the SPL response produced.
4. Notice that the pressure contours are always normal to the enclosure walls and for the axial modes the profile is normal to the axial path along the TL's length.
5. Since the velocity is the gradient of the pressure, the velocity at the boundaries will always be parallel to the enclosure walls.
6. Unlike a sealed or ported enclosure, the maximum pressure at resonance is very localized and not a constant throughout the enclosure volume. Less efficient excitation of the enclosure walls?
7. For the two plots on the right when the blue pressure profile, the solid line, and the dashed line intersect a null should be expected in the terminus SPL response. When the dashed line intersects the pressure profile near a peak, a maximum in the SPL output should be expected.

Mode	MathCad	ANSYS 3D	Measured	Description
Tuning --->	32	35	31	1/4 Wavelength
3	131	144	126	3/4 Wavelength
4	222	242	210	5/4 Wavelength
5	315	339	314	7/4 Wavelength
6	402	437	386	9/4 Wavelength
7	494	526	526	11/4 Wavelength
8	582	605	597	13/4 Wavelength
		680	640	1/4 Side to Side
		694	680	3/4 Side to Side
9	673	695	652	15/4 Wavelength
		721	725	5/4 Side to Side
		735	745	1/4 Front to Back
10	765	758	758	17/4 Wavelength
		760	786	7/4 Side to Side
		807	815	9/4 Side to Side
		860	857	11/4 Side to Side
11	841	873	894	19/4 Wavelength
		878	910	3/4 Front to Back
		910	932	13/4 Side to Side
12	943	938	953	21/4 Wavelength
	[Hz}	[Hz}	[Hz}	
ANSYS Model w/ Simple BC at the Terminus : p = 0 and du/dt = 0				

The table at the left compares the MathCad 1D model with an offset driver and acoustic BC at the terminus, the ANSYS 3D model without a driver and with the simple BC at the terminus, and the measured near field terminus SPL response (reality).

While it is obvious what each mode shape is in the analytical models, reviewing the test data and assigning a label was not always so straightforward. The modes in the table were matched by carefully looking at the peaks and dips, some judgement (particularly between modes 8 and 10) was used when correlating the results.

The table does not represent a completely apples to apples set of comparisons, each of the analytical models is missing a key ingredient that is present in the measured test data. The driver, the 3D geometry, and the correct acoustic boundary condition at the terminus are never all present in either computer simulation. But the results are all close enough (within about 5% or less) to be considered an accurate representation of the measured test results, and therefore demonstrate the air behavior along the length of the TL enclosure.

From the results shown on Slide 13, the 1D model is an accurate representation of the TL behavior up to the onset of 3D motions. The peaks and nulls line up well below 400 Hz. Above 400 Hz, the ANSYS 3D model is a better representation of the various modes but not a good indicator of the magnitude of the SPL response.

Reviewing the frequencies tabulated on the previous slide, and the plotted results shown in Attachment 2, several observations are made.

1. The resonant frequencies and mode shapes in the axial path direction for the TL correlate well between the MathCad and ANSYS simulations. This is evident by comparing the pressure profiles along the two paths in Attachment 1 with the pressure profile plotted in Attachment 2 for corresponding modes.
2. The important results shown in Attachment 2 are the magnitude of the pressure, volume velocity, and displacement of the oscillating air for a 2.828-volt input (1 watt into 8 ohms). This helps quantify the air behavior in a TL. After studying the mode shapes shown in Attachment 2, observations can be made about what postulated air behaviors really exists and what are incorrect speculations.
3. The non-axial modes calculated by the ANSYS model, shown in Attachment 1, are weakly coupled to the driver. The driver is centered so it is on a pressure null for the side-to-side modes and in a region of low oscillating pressure for the front-to-back modes. Also recognize that at these higher frequencies the oscillating pressure, volume velocity, and displacement will have much lower magnitudes compared to the first few axial modes.
4. While the modes below 400 Hz correlate well with the measured results, above 400 Hz the measured SPL is on average 5-10 dB lower than the MathCad predictions. There are three potential causes that come to mind. Inaccurate acoustic modeling of the 180-degree bend, the non-axial modes combining with and diluting (resulting from phase differences between the modes) a portion of the axial mode’s response, or damping introduced by the foam used to seal the enclosure (not very likely IMO). Since the magnitude of the peaks for the modes below 400 Hz correlate well, I do not believe there are geometric induced acoustic losses introduced by the folding of the TL path that would account for this 5-10 dB difference. The first and second potential causes seem to be the most likely contributors to the reduced SPL output.

Key Take Aways from Part 2

1. The important standing waves that shape the Satori TL's low frequency response and any ripple in the SPL response are those below the 9/4 wavelength mode, in this case the modes below 400 Hz. Above 400 Hz the fiber damping and the crossover control the Satori TL's SPL response.
2. The mode shapes of the quarter wave resonances are like an accordion, the stretching and compressing of the air produce small changes in pressure and small axial displacements. Using modal analysis, any pressure and displacement profile in the TL can be decomposed into a linear combination of these quarter wave mode shapes.
3. Considering the oscillating pressure profile of each mode, and thinking about summations of multiple modes, a few often claimed behaviors can be ruled out. There are no laminar or turbulent flows, no vortices produced, no separation of an air layer in the folds, and no dead zones in the corners. There are just **very small local back and forth axial oscillations** of the air without any net flow or other fluid dynamics behaviors.
4. There are no broad band reflections of sound off the rear wall coming back to the driver and then transmitting through the cone. The only significant reflection present in a TL is at the terminus boundary condition which is required to generate axial standing waves. The axial standing waves can produce enough back pressure to impact the driver's cone motion, but this is at specific frequencies and is not a broad band reflection as commonly described on the various DIY speaker design forums. Nonparallel walls do not eliminate enclosure resonances and standing waves, they just change the frequencies of the resonances.
5. The behavior of the air vibration through the folds in the TL is not handled cleanly by the 1D wave equation used in almost all TL simulation software. The 1D wave equation is not valid for folded geometries (the more folds the more inaccurate the simulation). The next study, Part 3, will show the concerns and hopefully produce some recommendation to improve modeling accuracy. But for right now, the simple 1D models of a single- or two-fold TL can produce accurate enough results so an enclosure can be designed with reasonable expectations of success.
6. Adding fiber damping reduces the peaks and nulls in the system SPL response as seen by comparing the plotted terminus results on slides 11 and 12, which will further reduce the magnitudes of the oscillating air motions shown in Attachment 2 significantly.

References

Complex Variables and Applications 8th Edition by Brown and Churchill, McGraw Hill, 2009

Acoustics : Sound Fields and Transducers by Beranek and Mellow, Academic Press, 2012

Modal Testing : Theory and Practice by Ewins, Research Studies Press, 1986

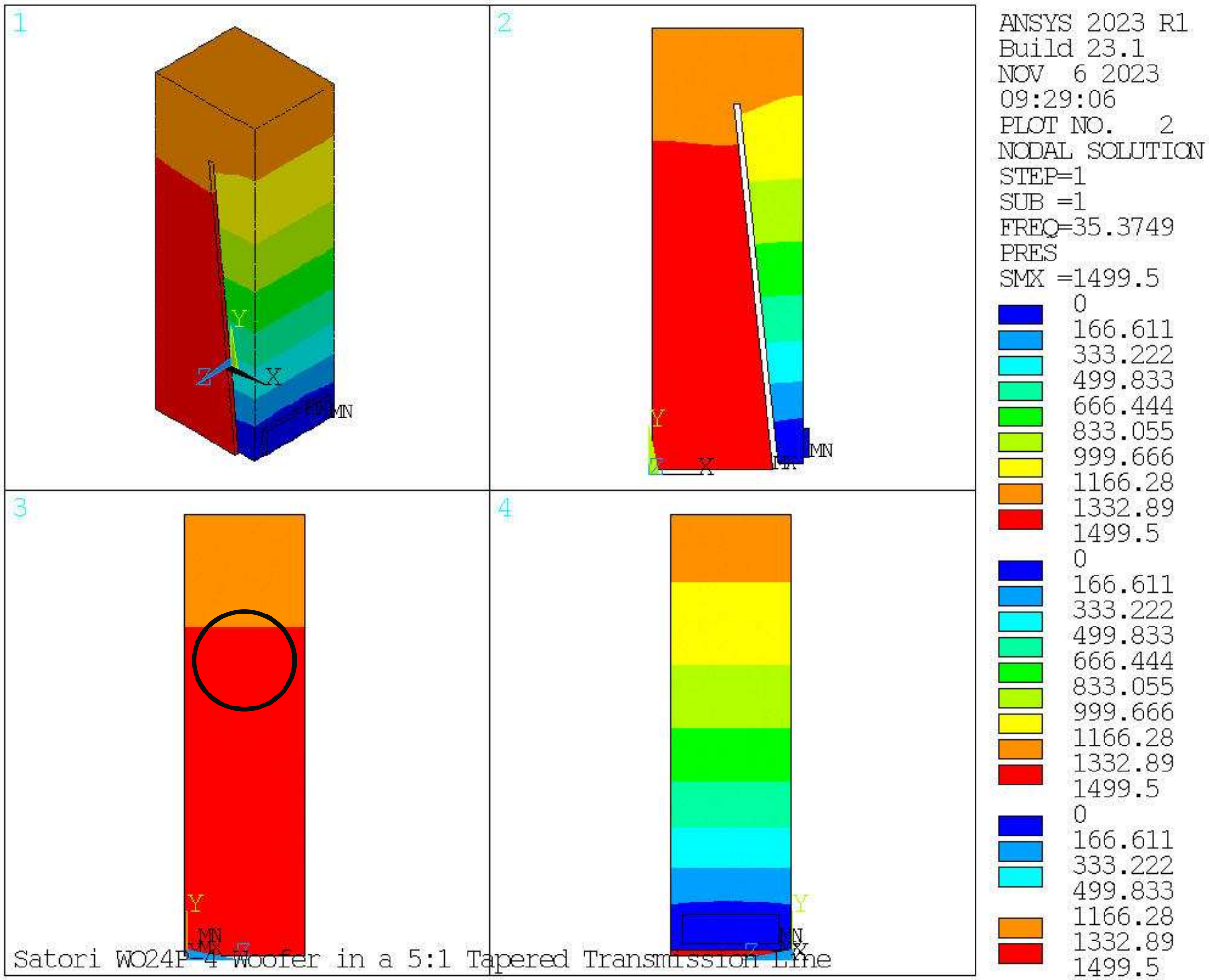
The Fast Fourier Transform by Brigham, Prentice – Hall, 1974

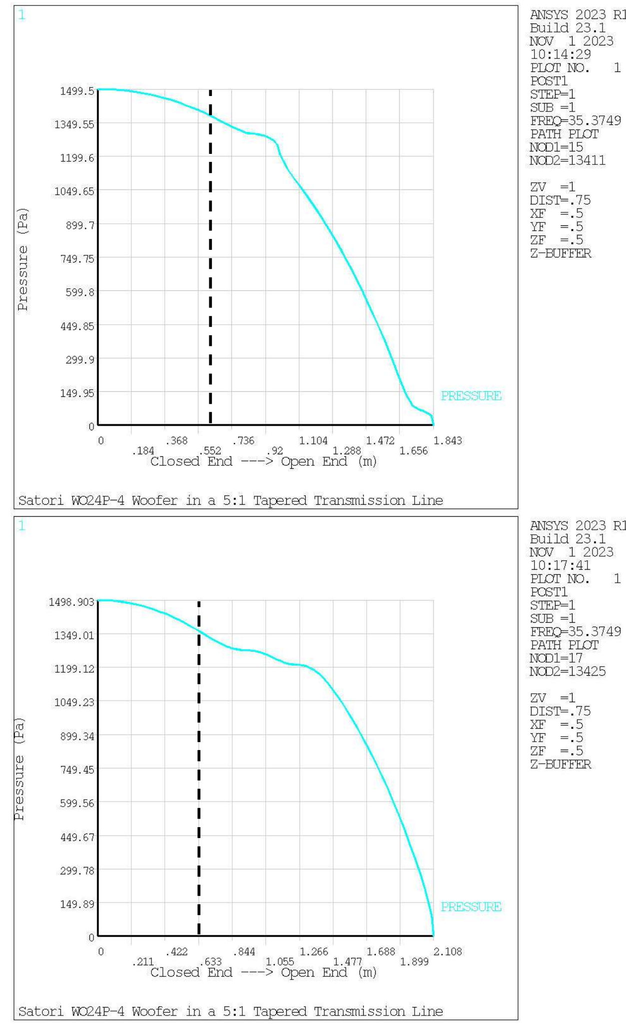
Engineering Vibration 4th Edition by Inman, Pearson, 2014

Attachment 1 : ANSYS 3D Model Results

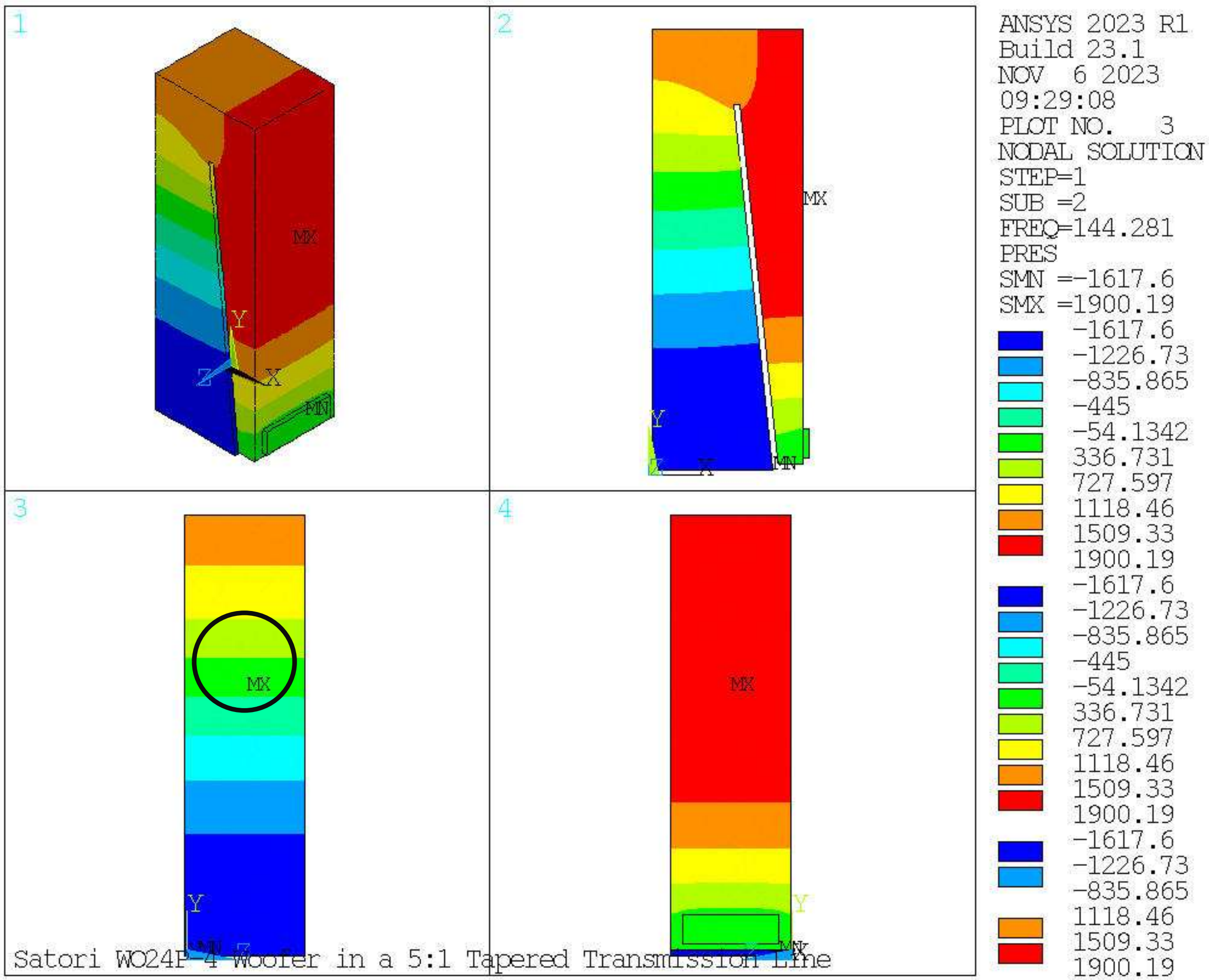
Each page contains a calculated resonant frequency, mode shape pressure contour plot viewed from different angles (left larger plot), and the pressure profile along an inner path (top right plot) and an outer path (bottom right plot) from the closed end to the open end. In each pressure contour plot, the front view (lower left plot) has the woofer location outlined by a black circle. In the pressure profile plots, a dashed vertical line is added to show the offset woofer's axial position and a solid horizontal line is placed at zero pressure.

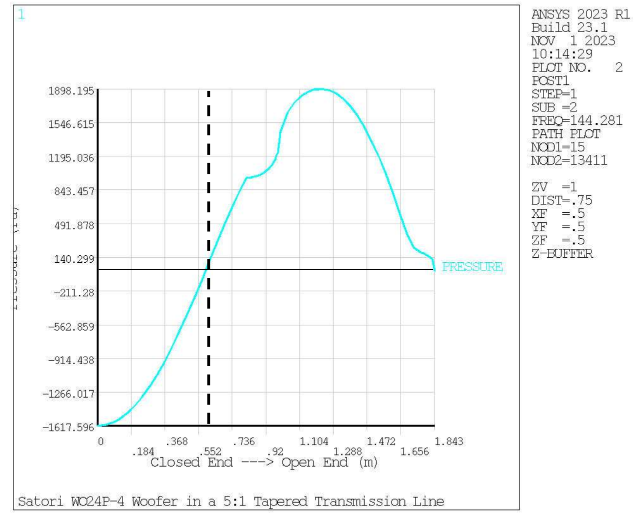
Axial Tuning Frequency – 35.4 Hz

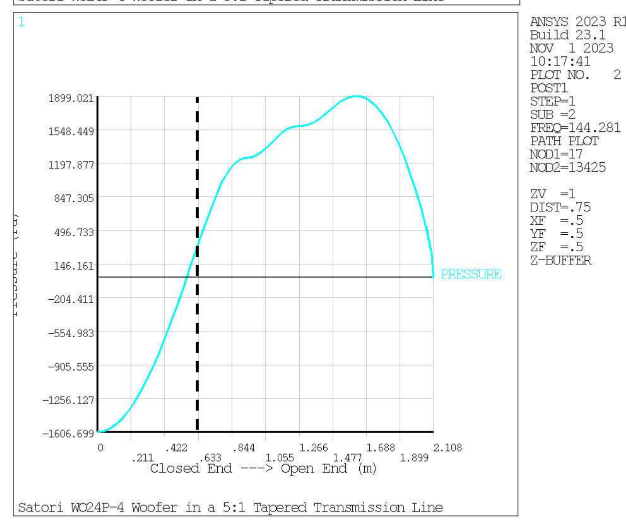




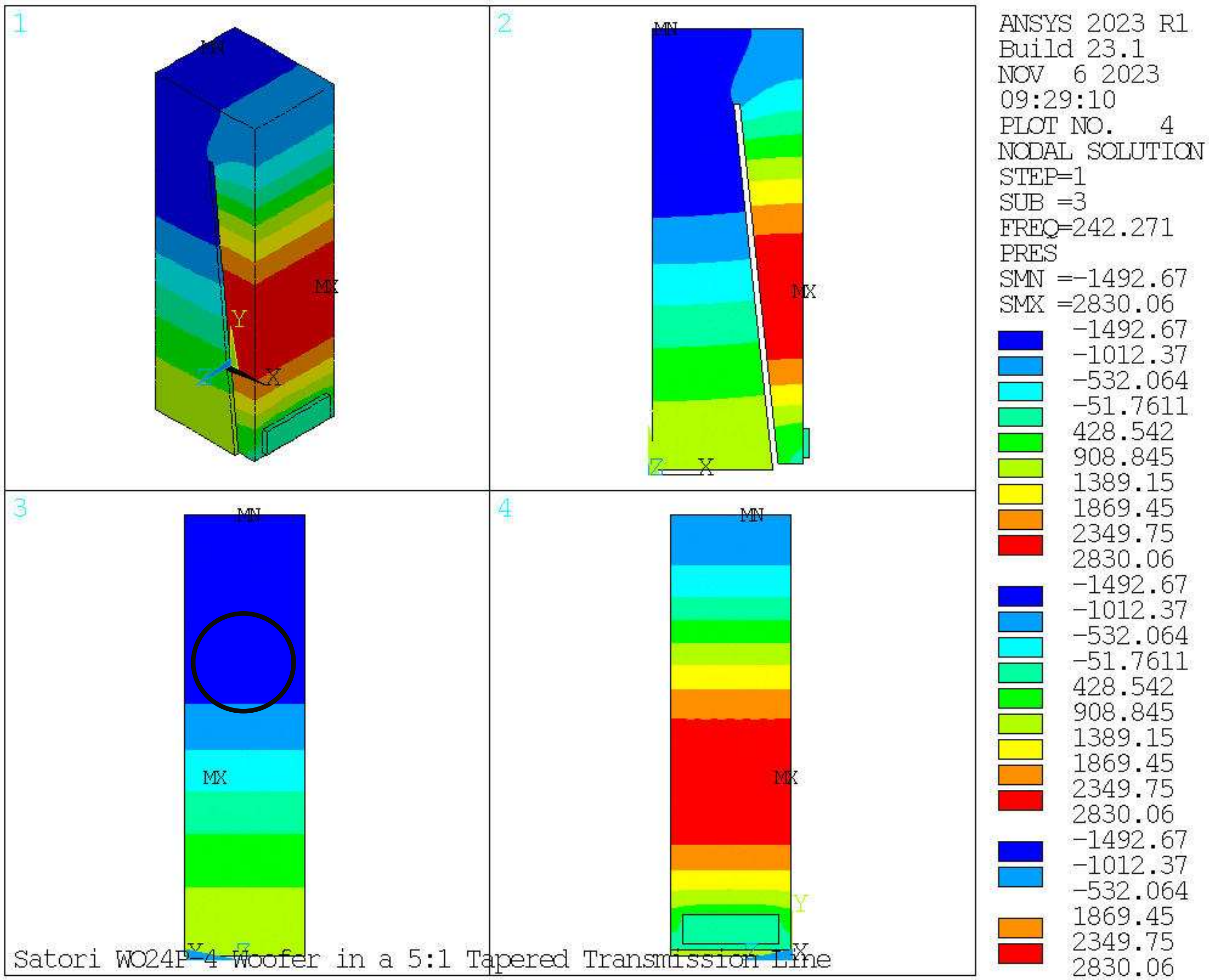
Axial Mode 3 – 144.3 Hz

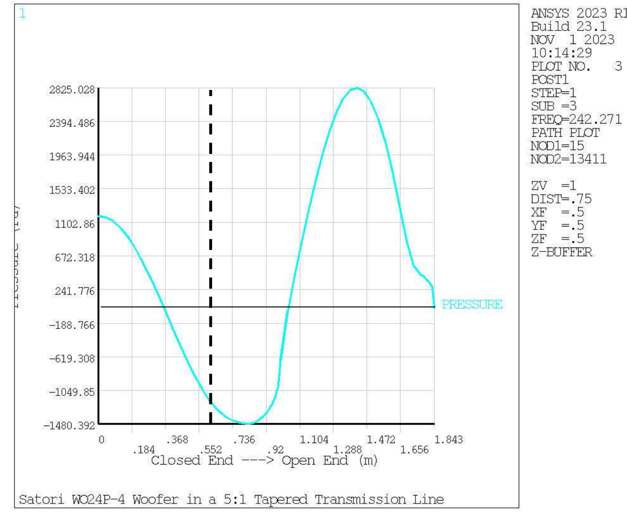


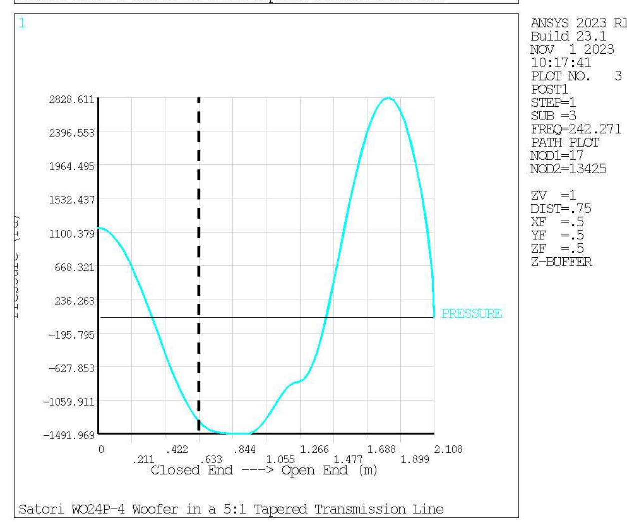




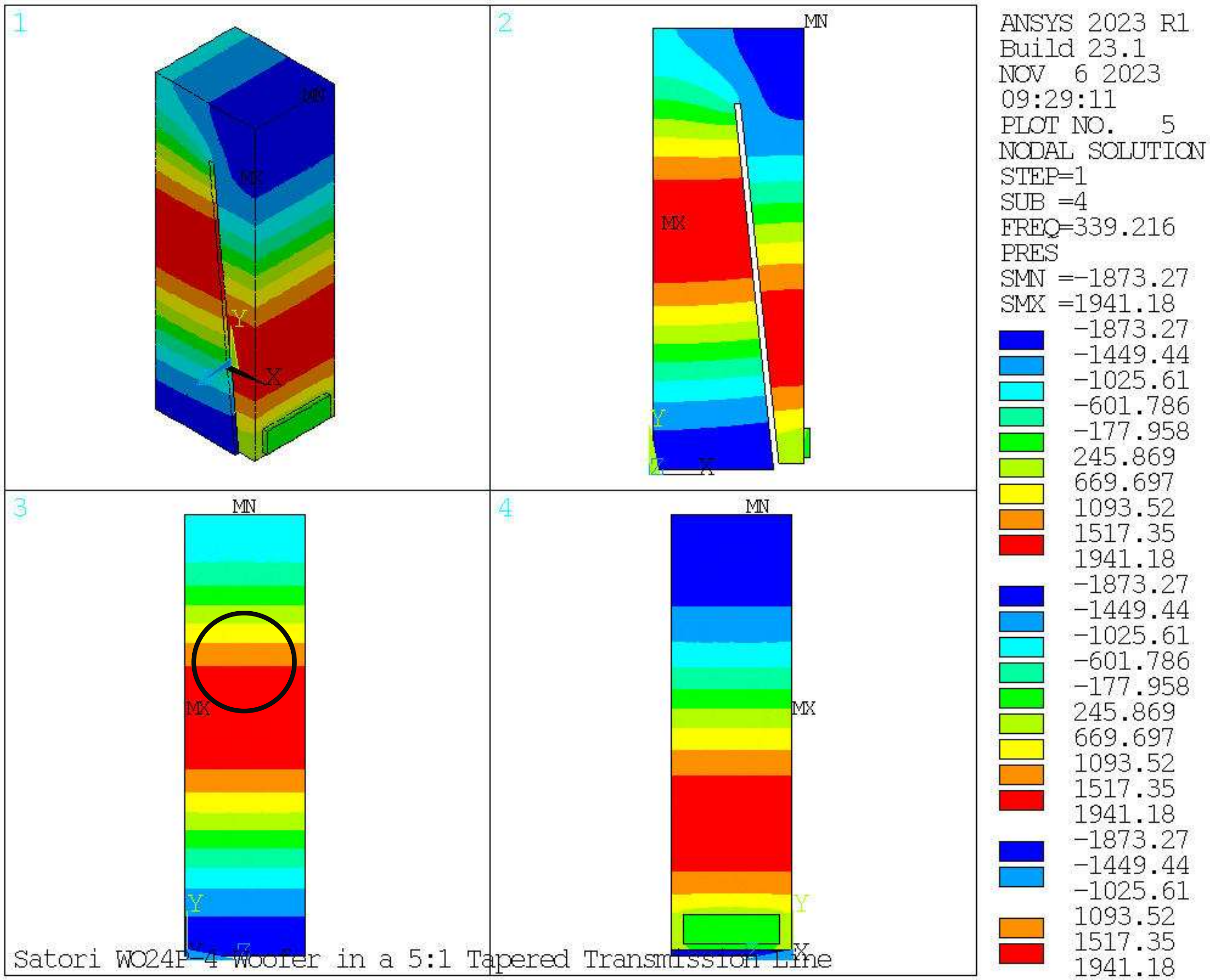
Axial Mode 4 – 242.3 Hz

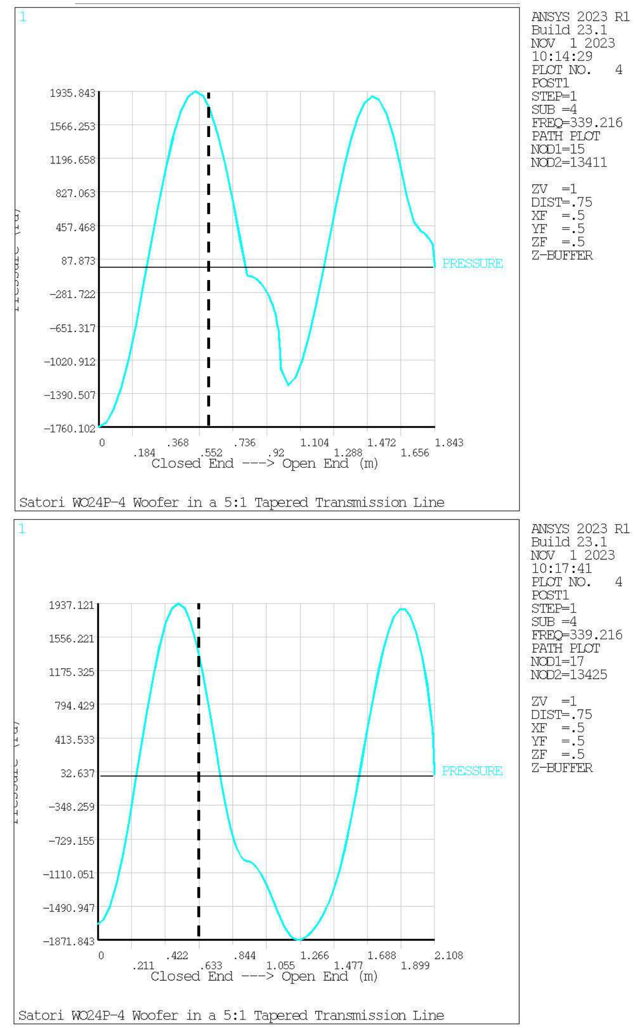




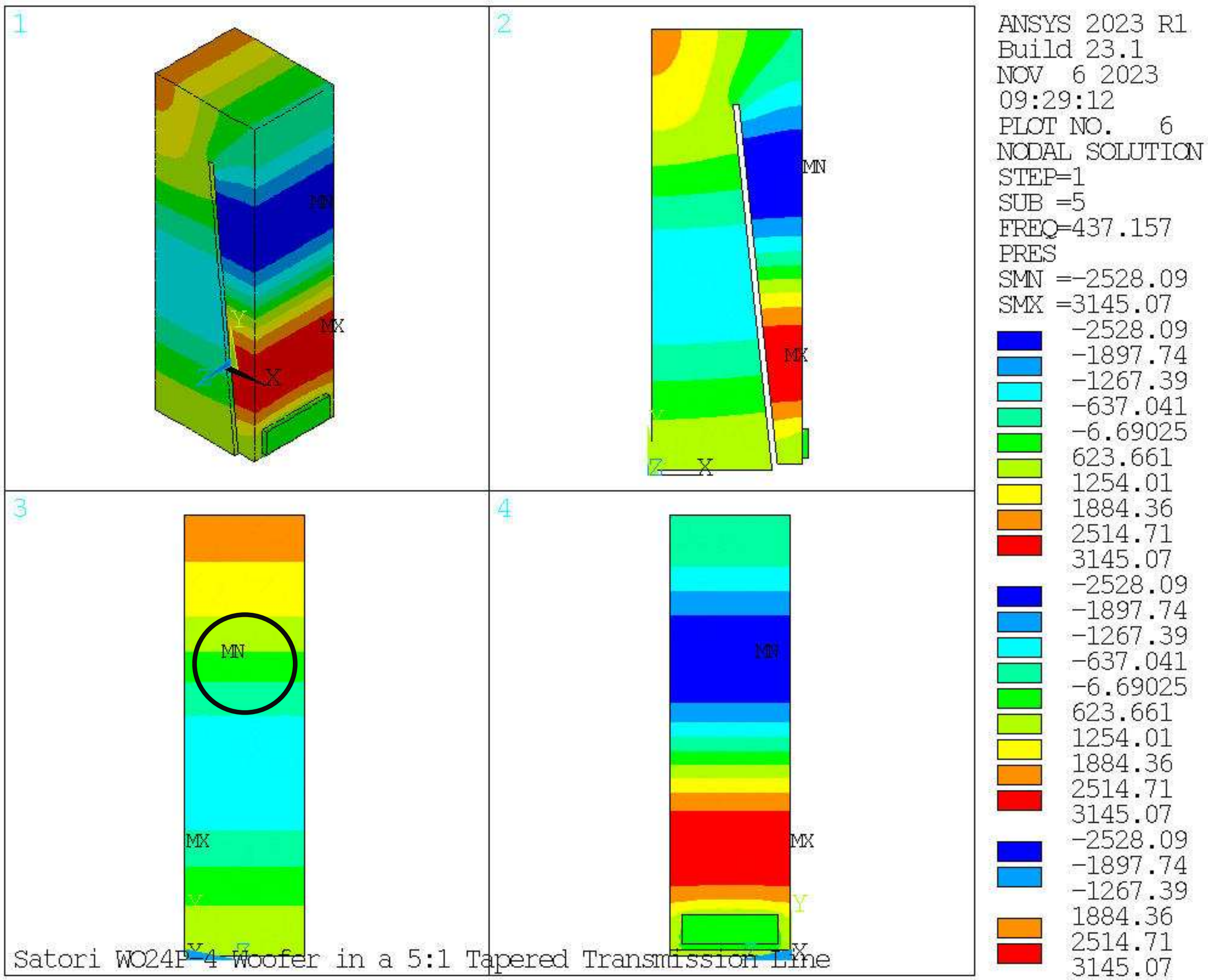


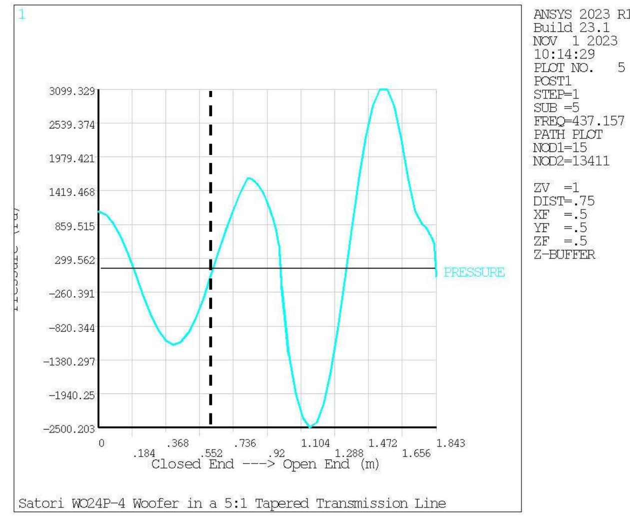
Axial Mode 5 – 339.2 Hz

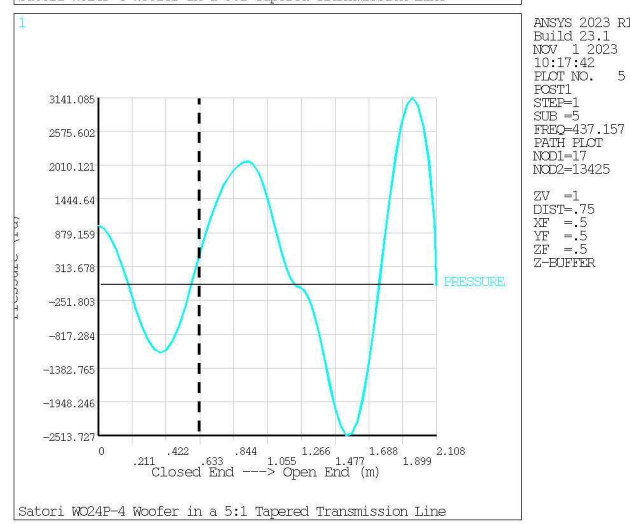




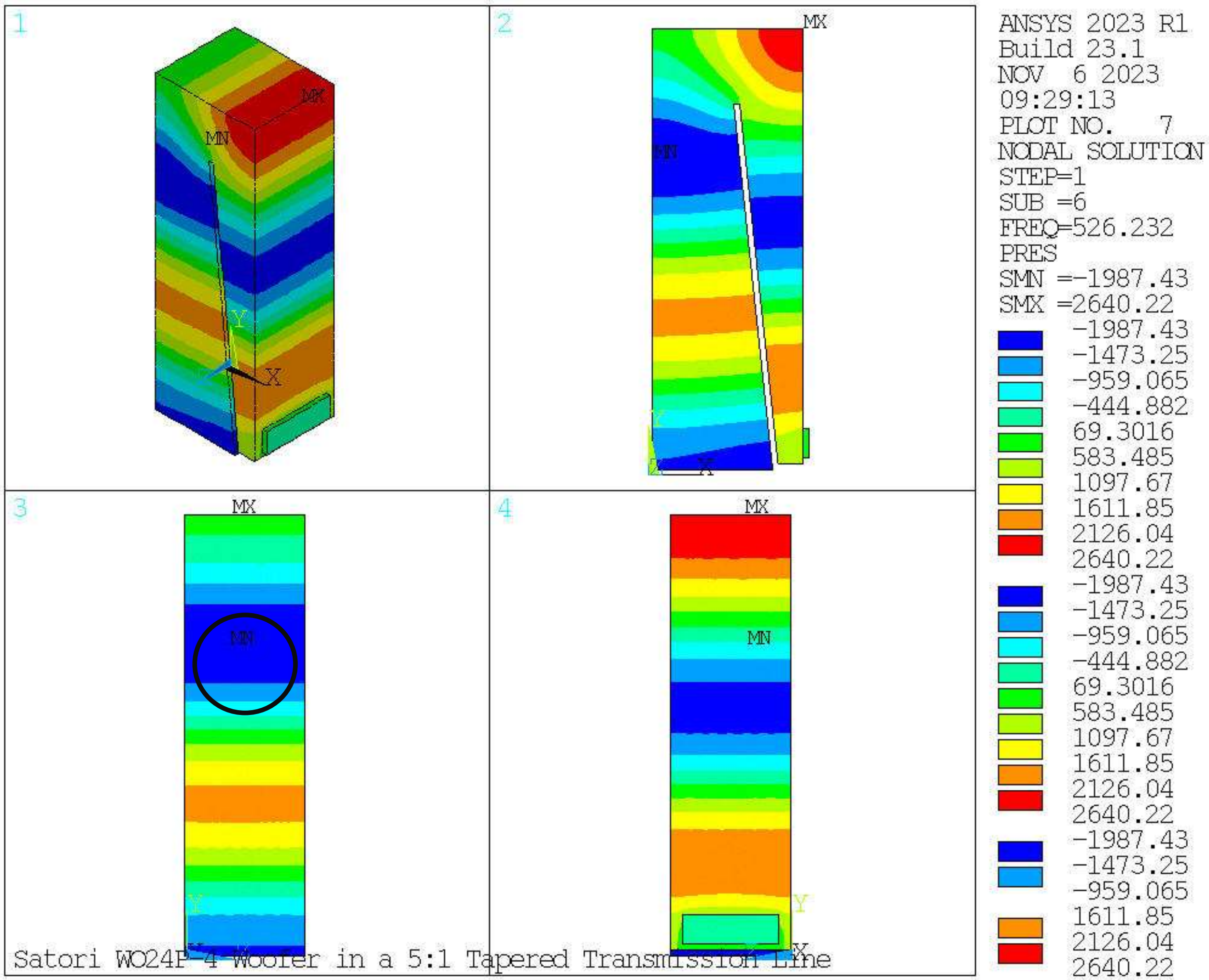
Axial Mode 6 – 437.2 Hz

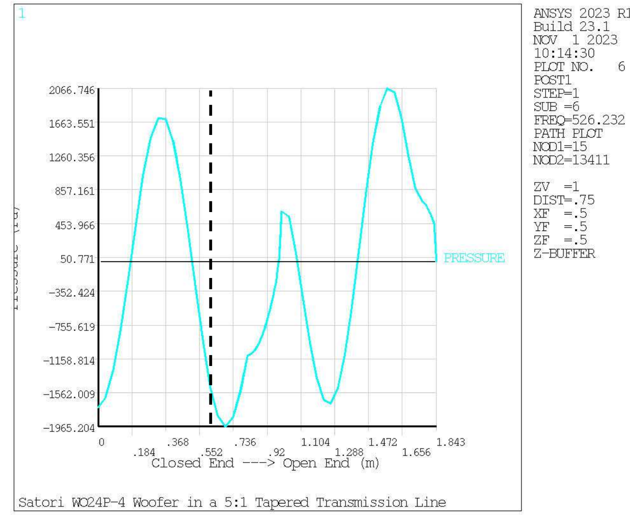


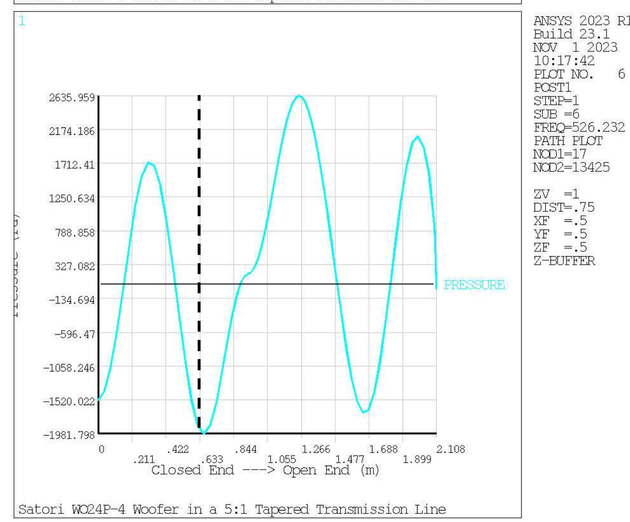




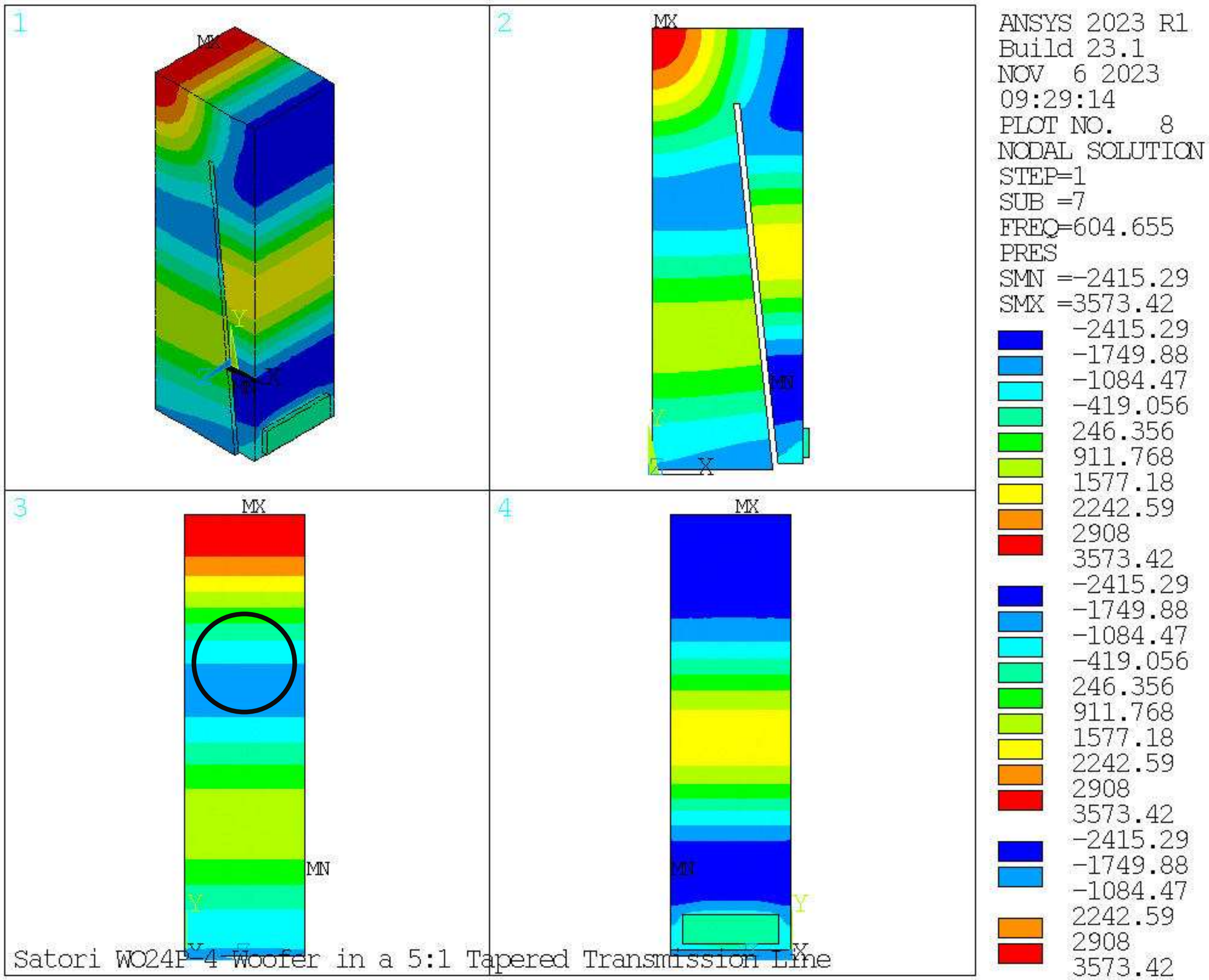
Axial Mode 7 – 526.2 Hz

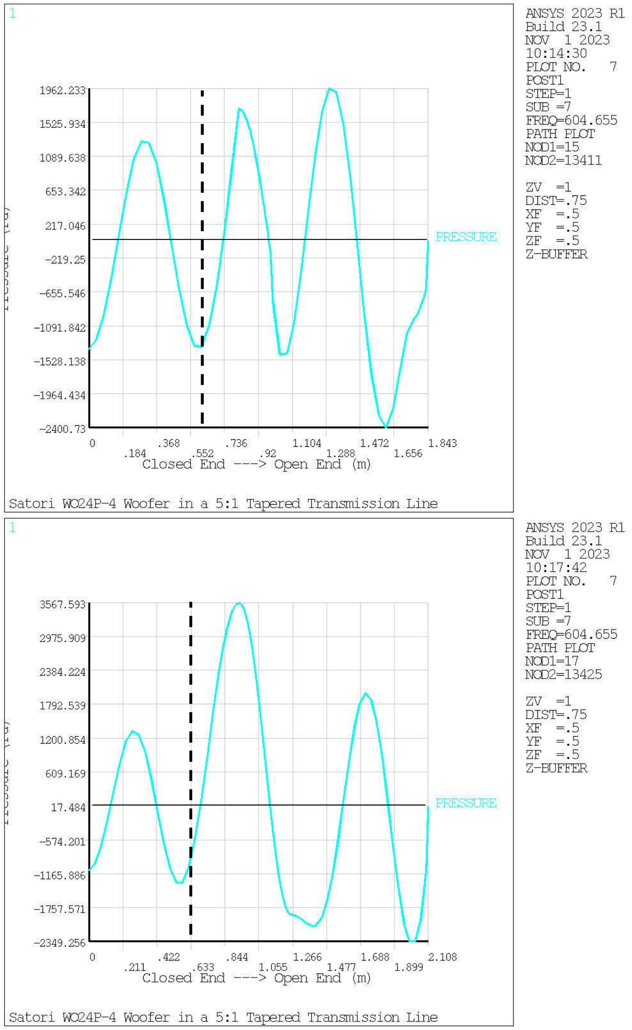




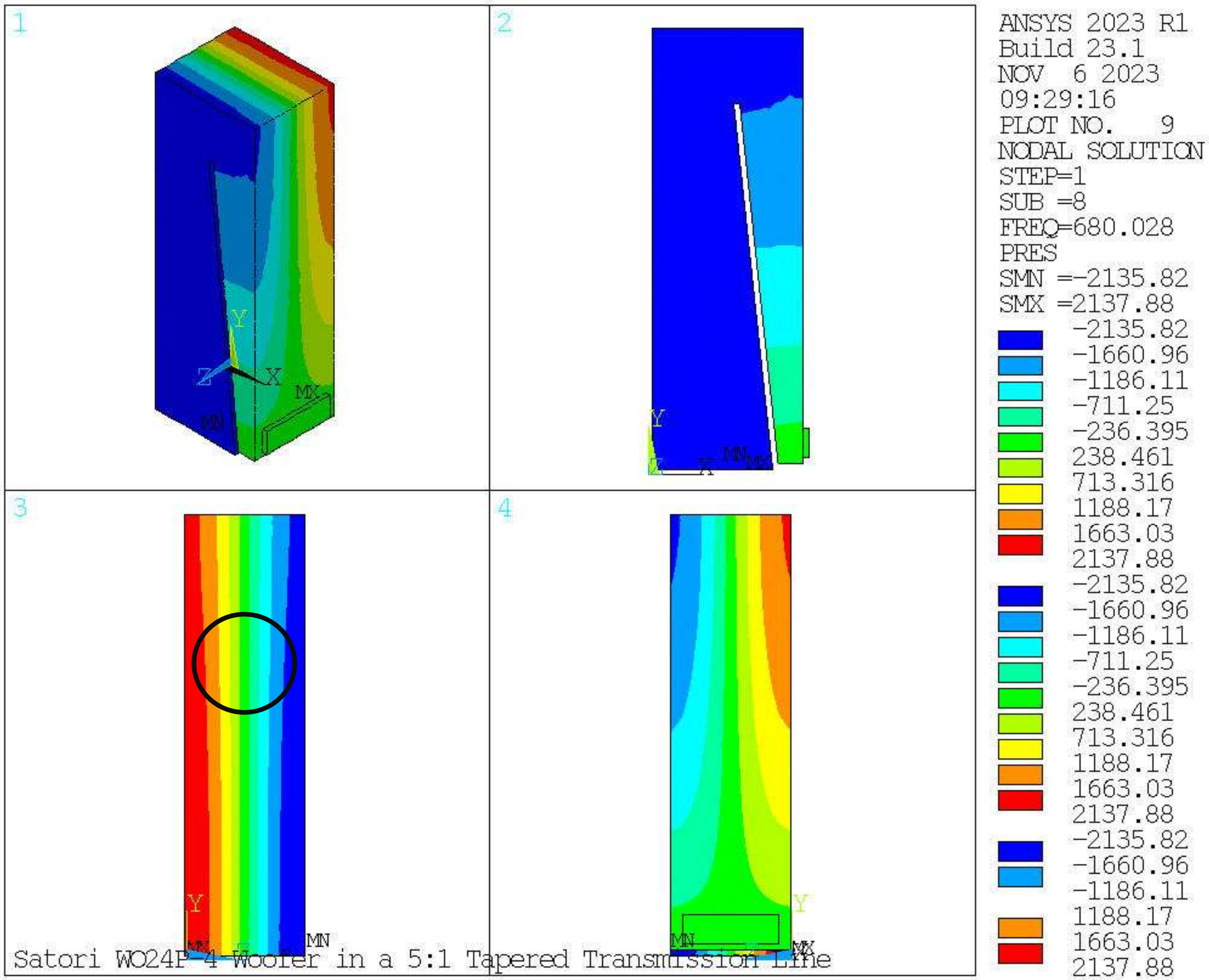


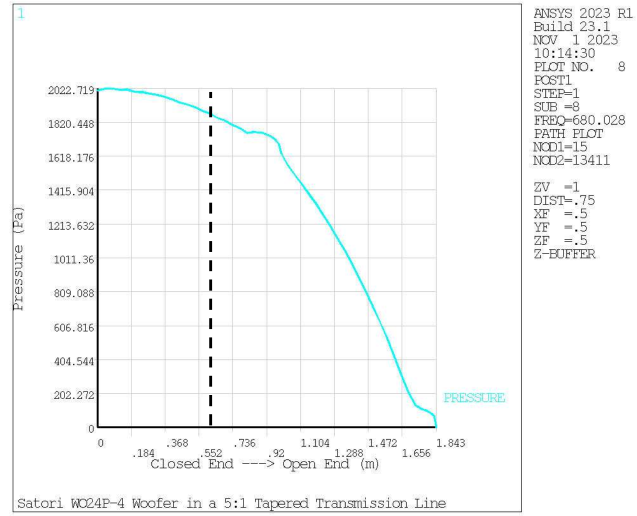
Axial Mode 8 – 604.7 Hz

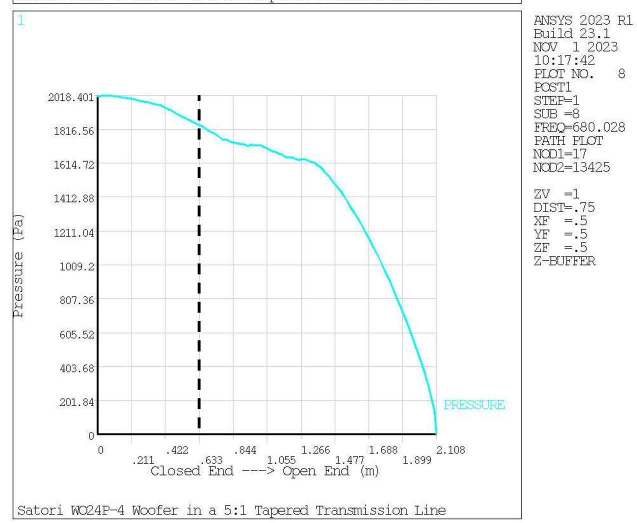




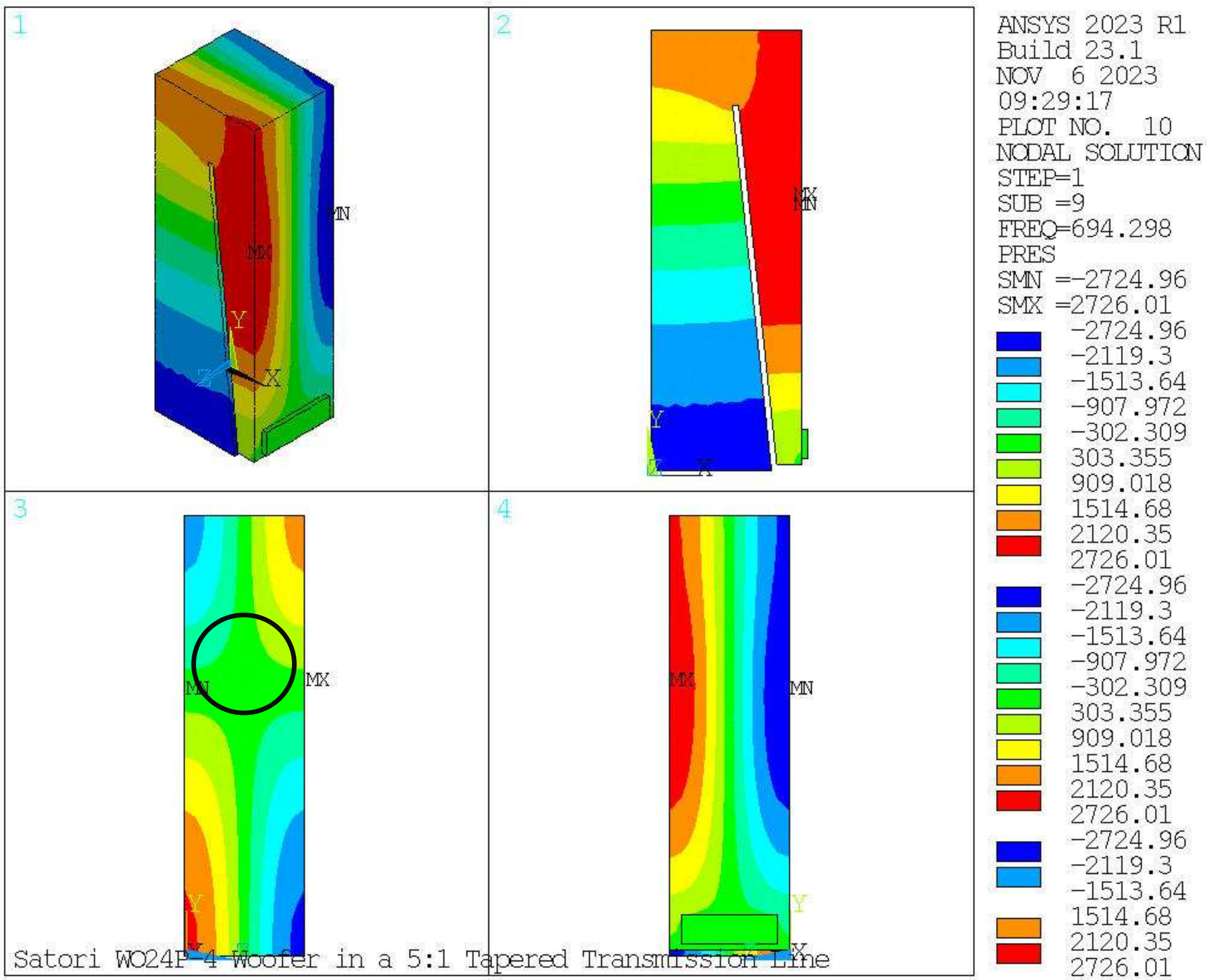
Side to Side – 680.0 Hz

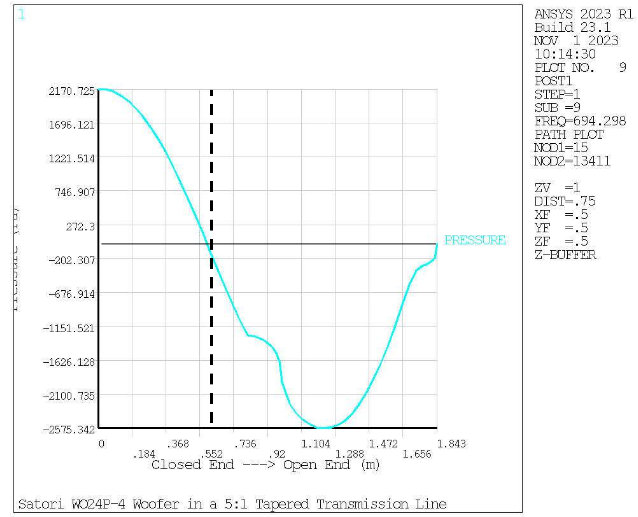


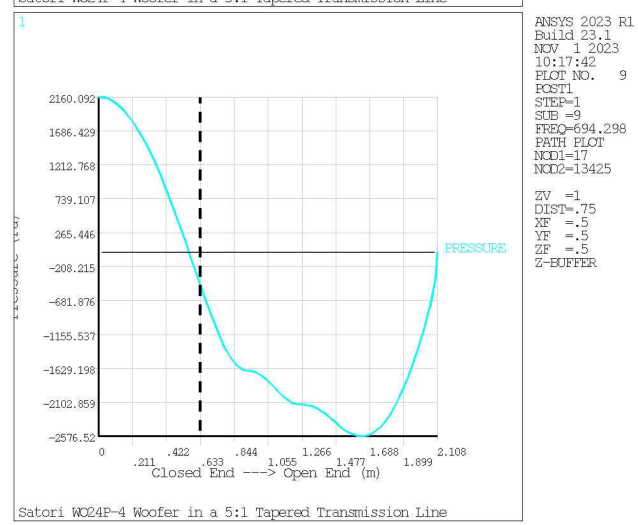




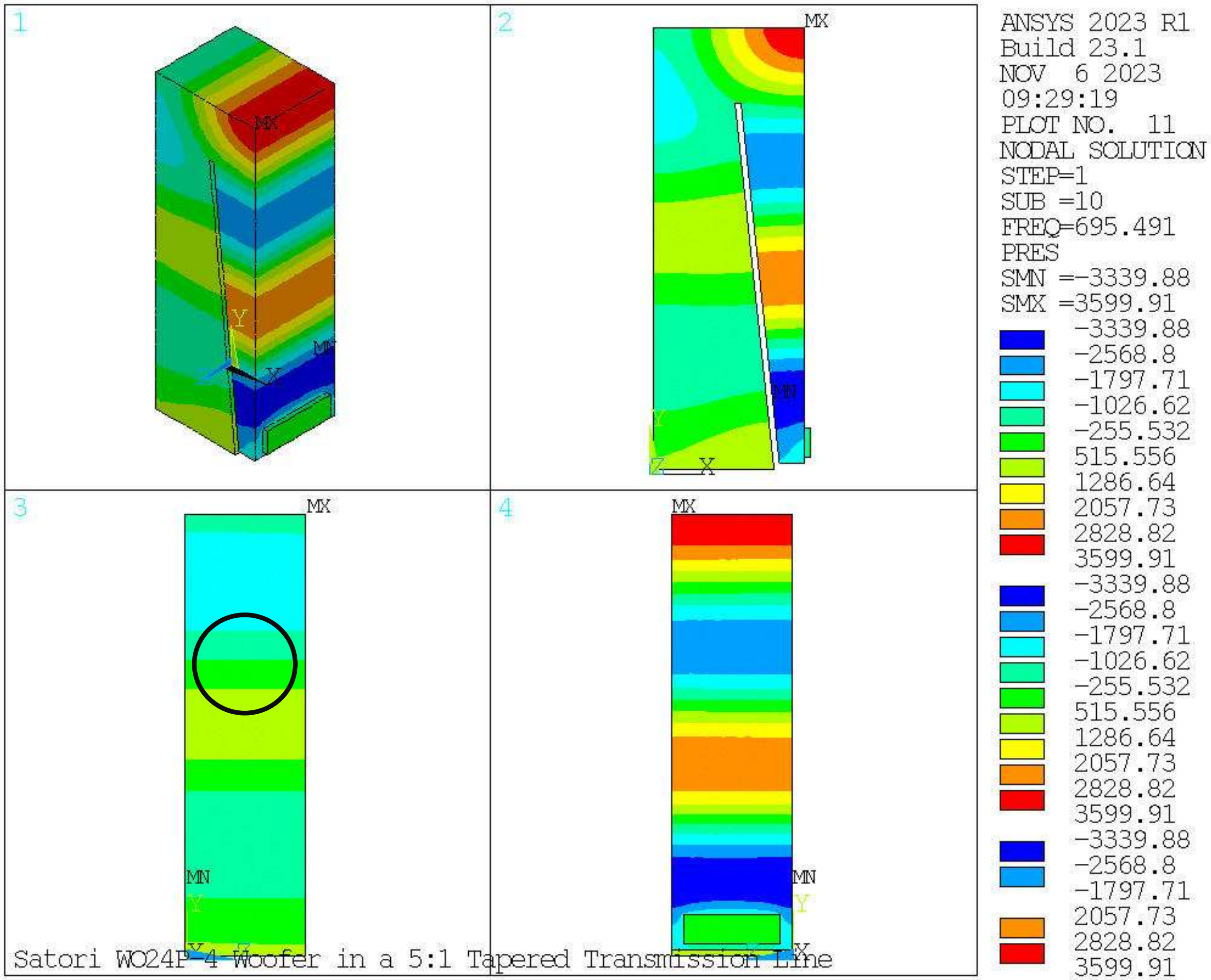
Side to Side – 694.3 Hz

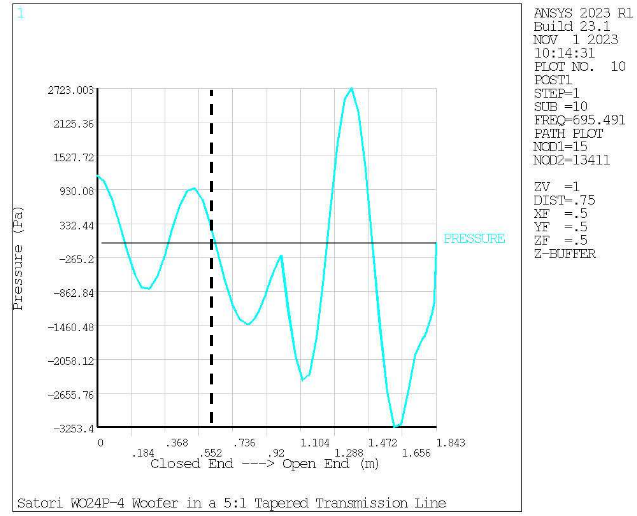


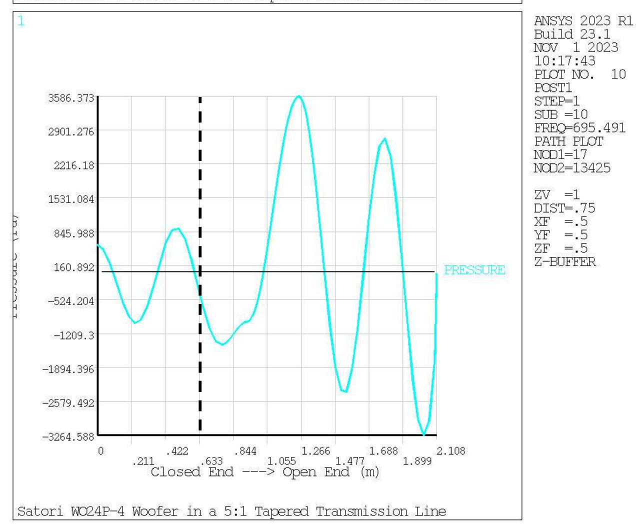




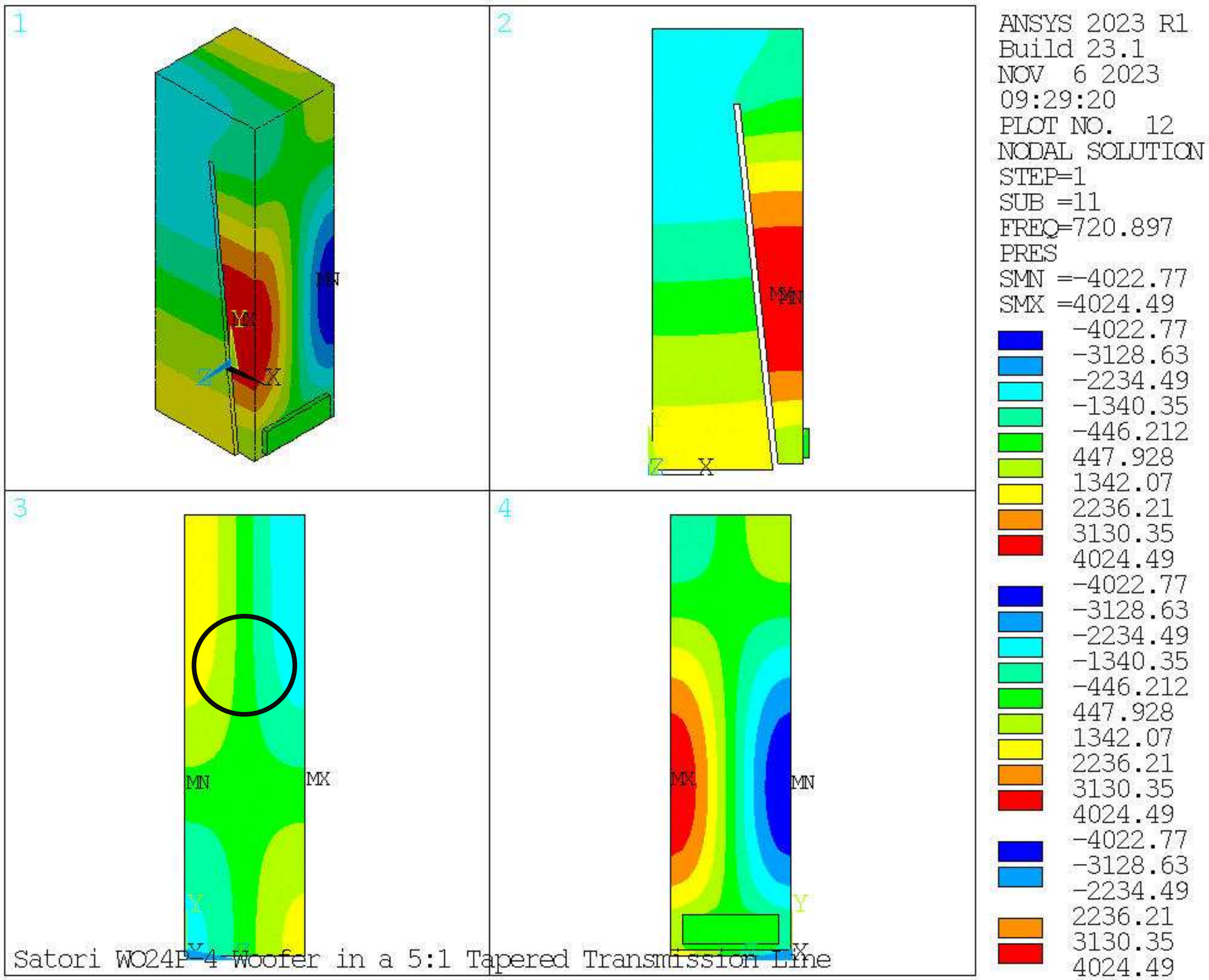
Axial Mode 9 – 695.5 Hz

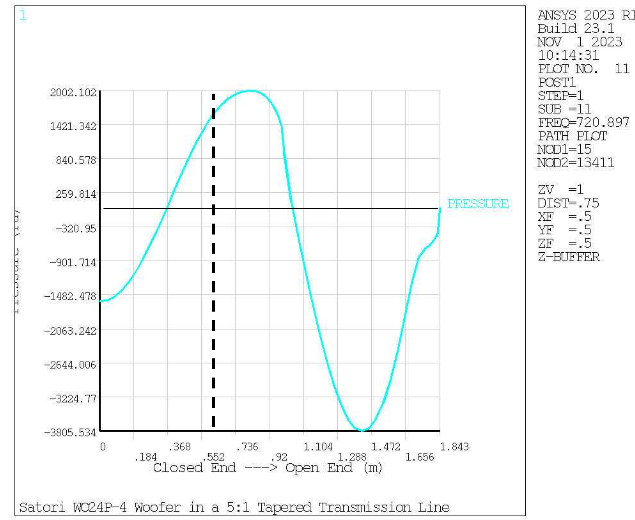


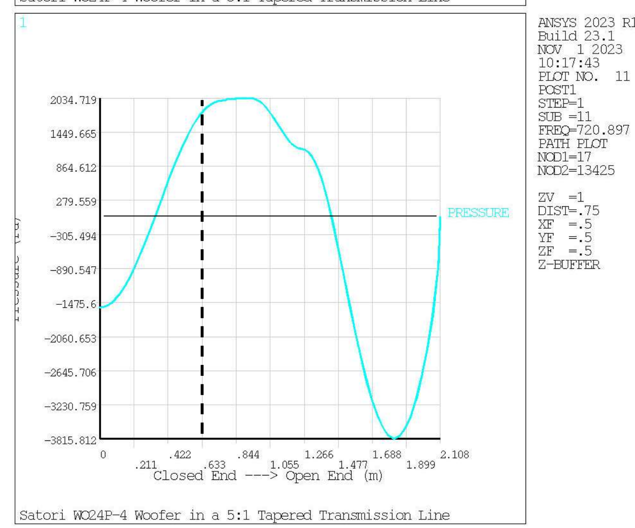




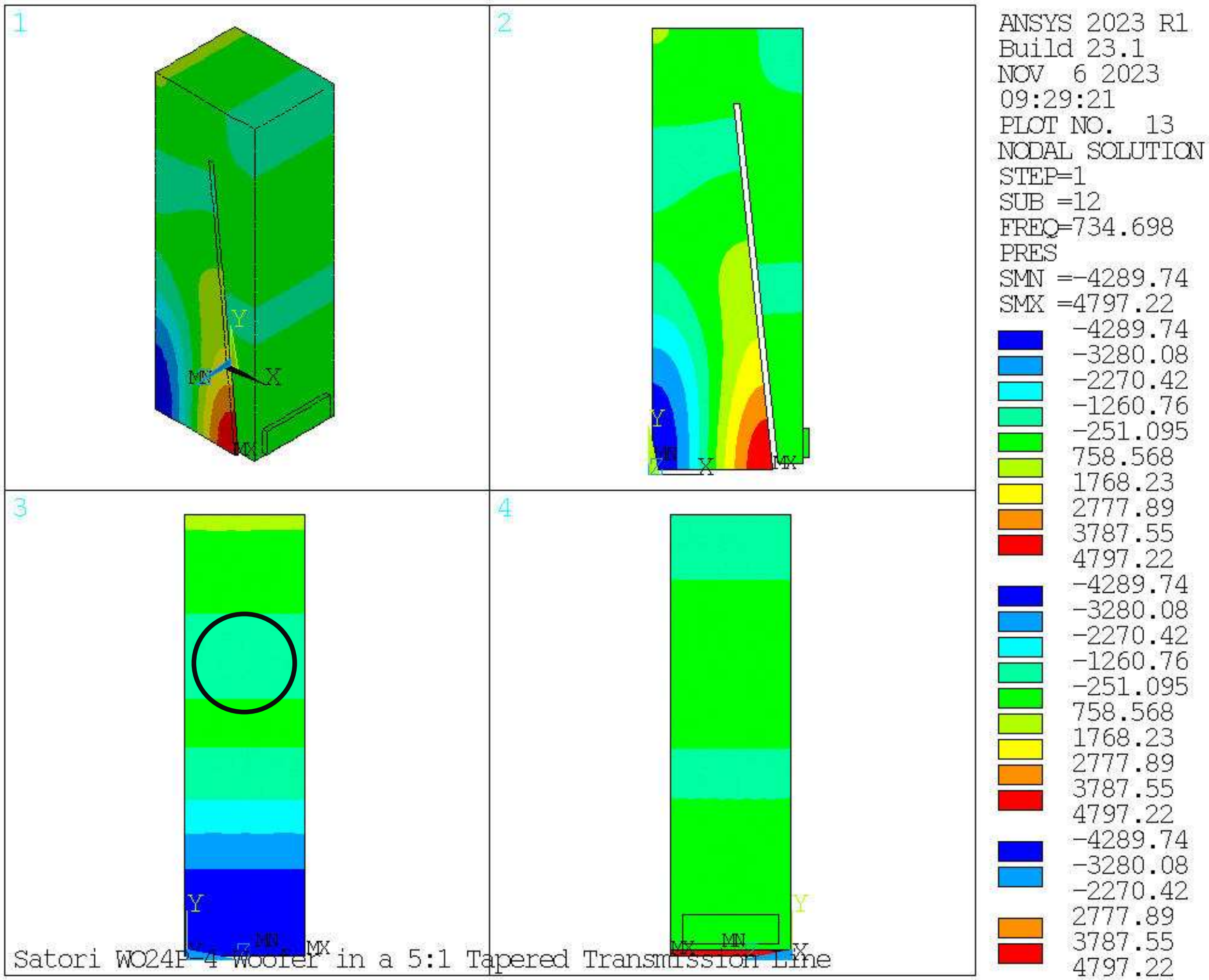
Side to Side – 720.9 Hz

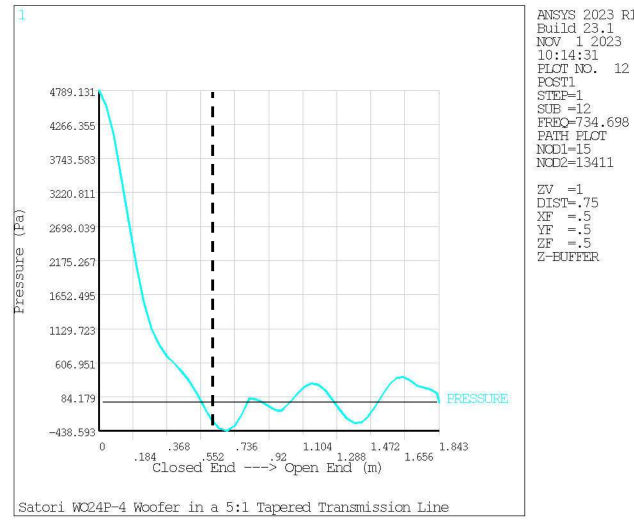


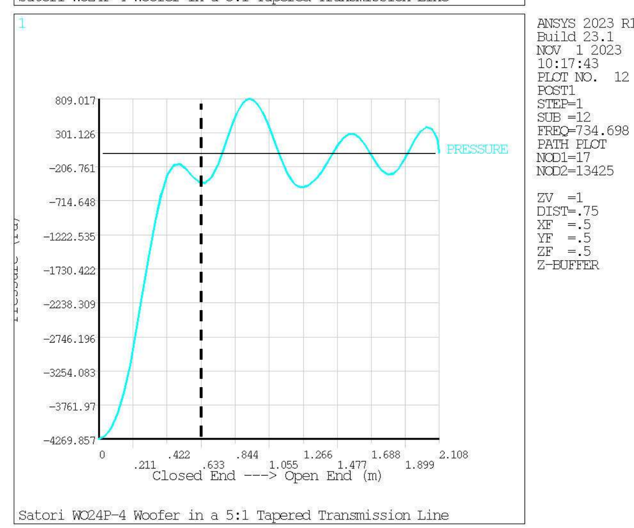




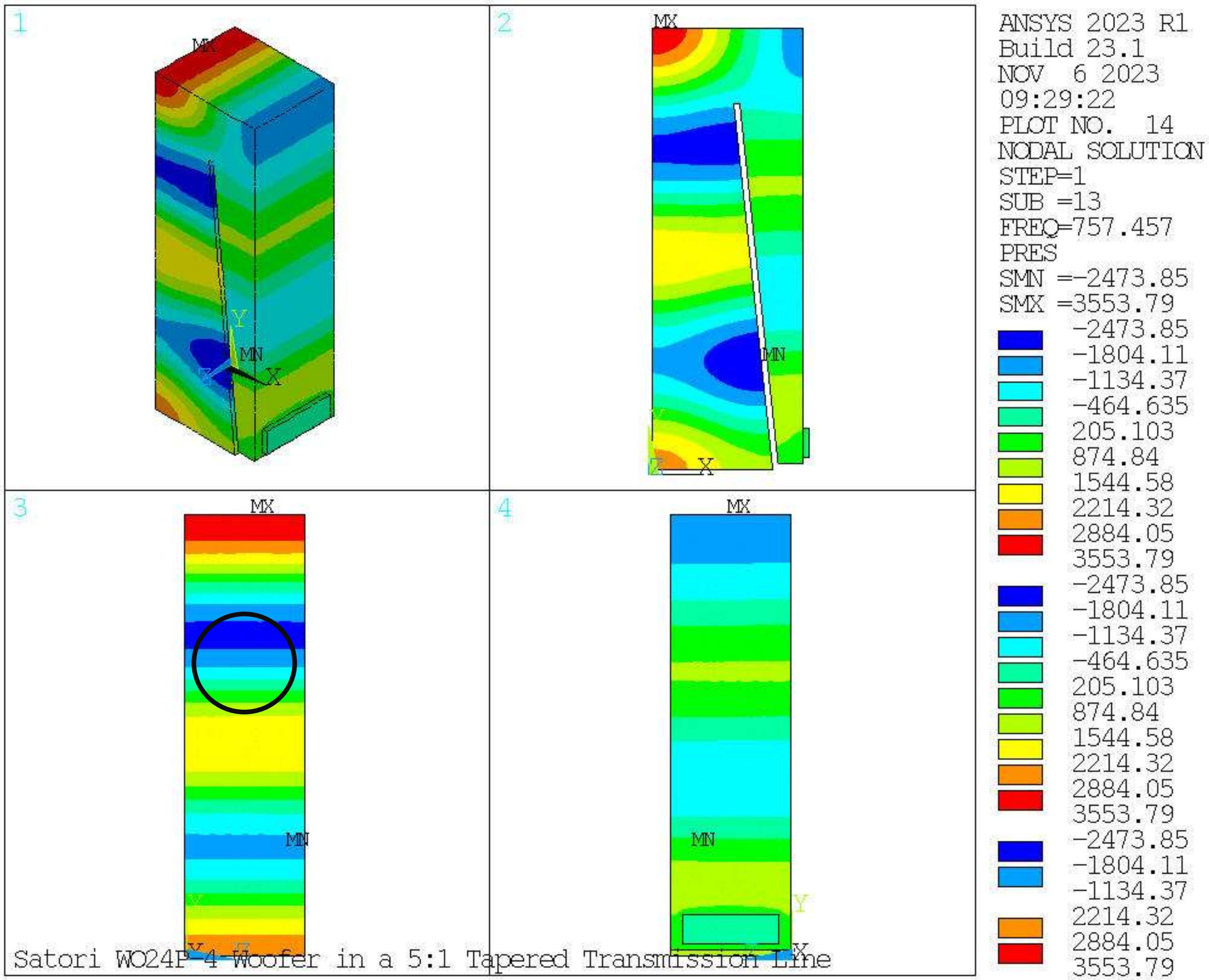
Front to Back – 734.7 Hz

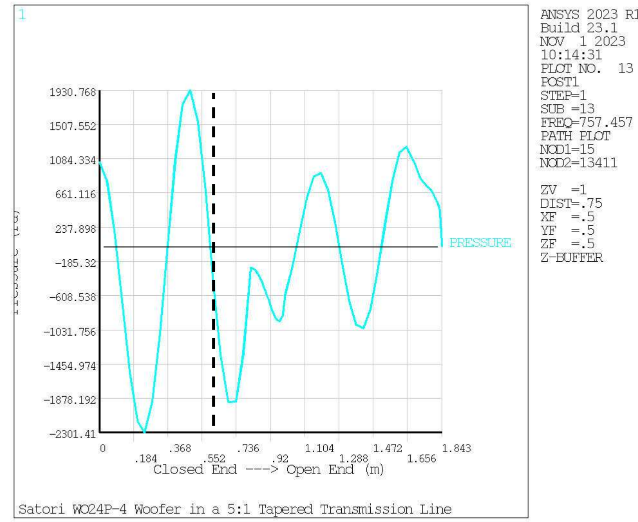


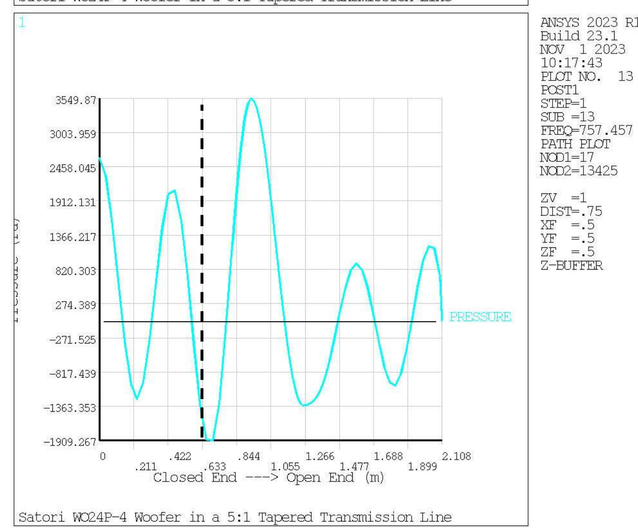




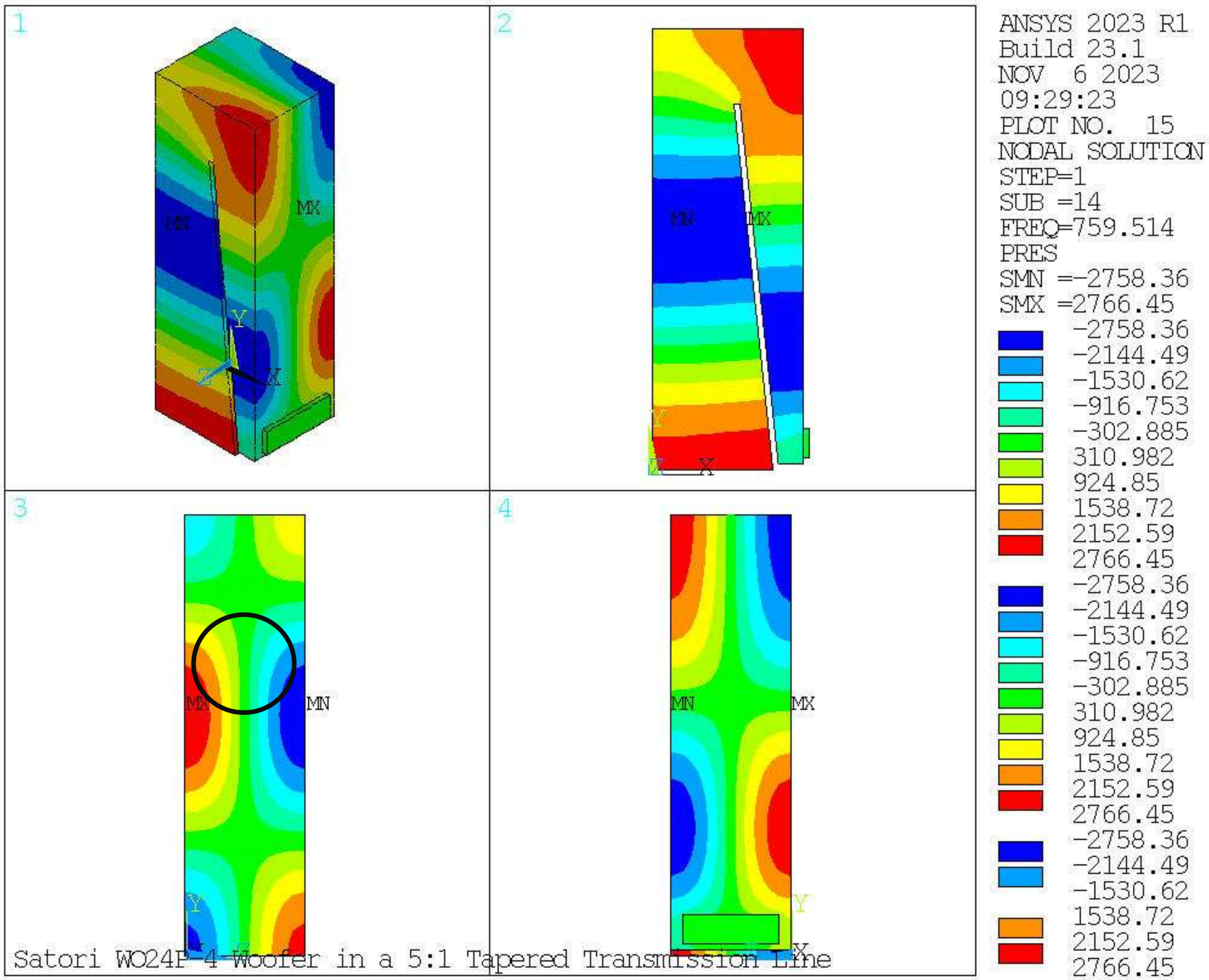
Axial Mode 10 – 757.5 Hz

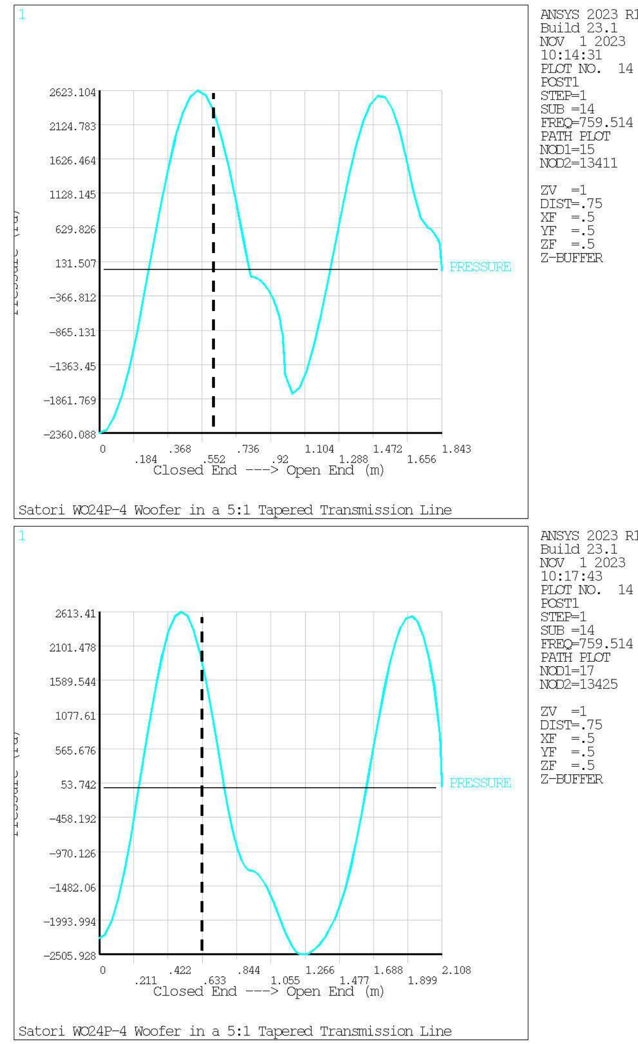




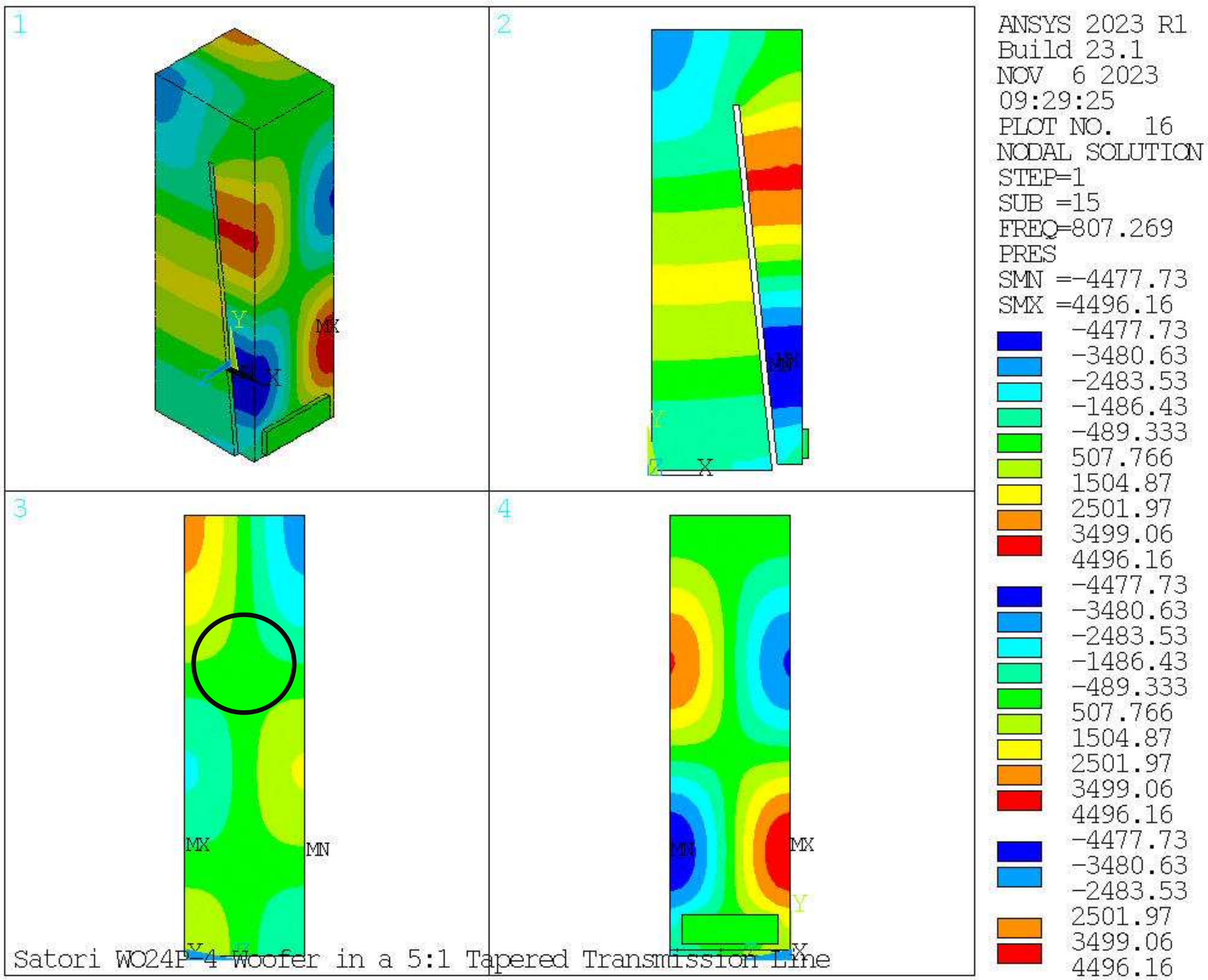


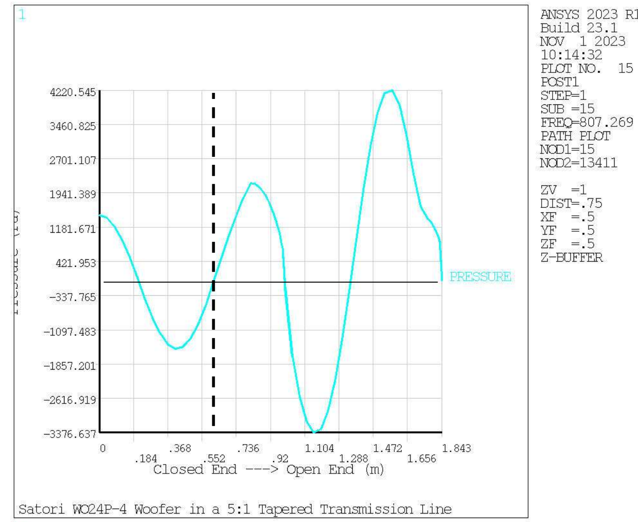
Side to Side – 759.5 Hz

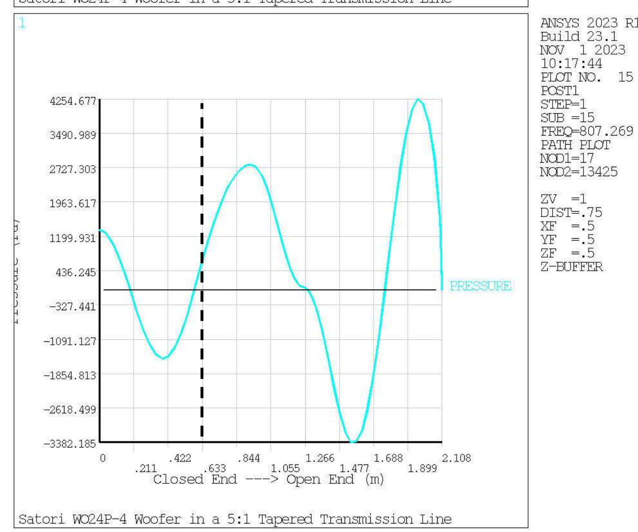




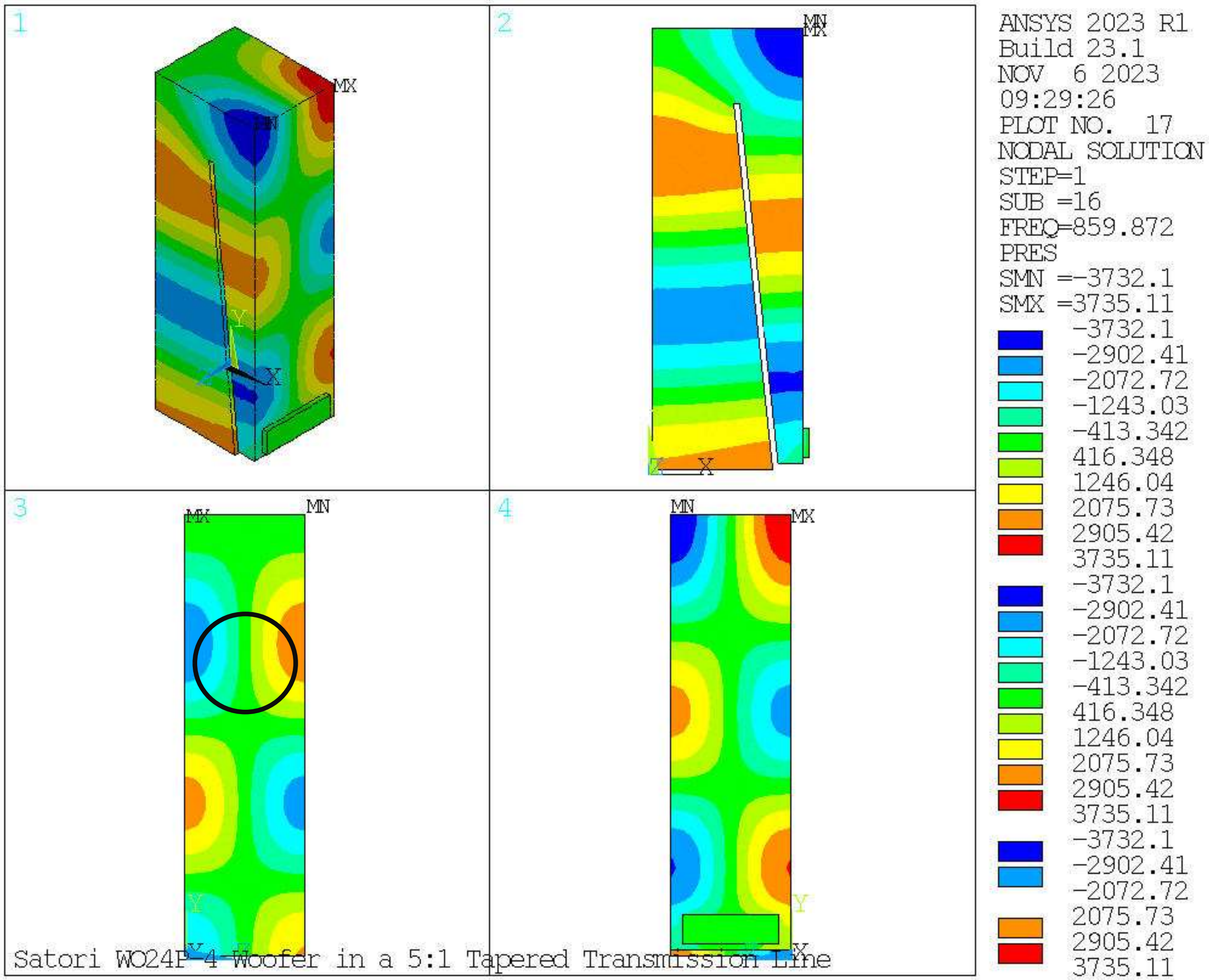
Side to Side – 807.3 Hz

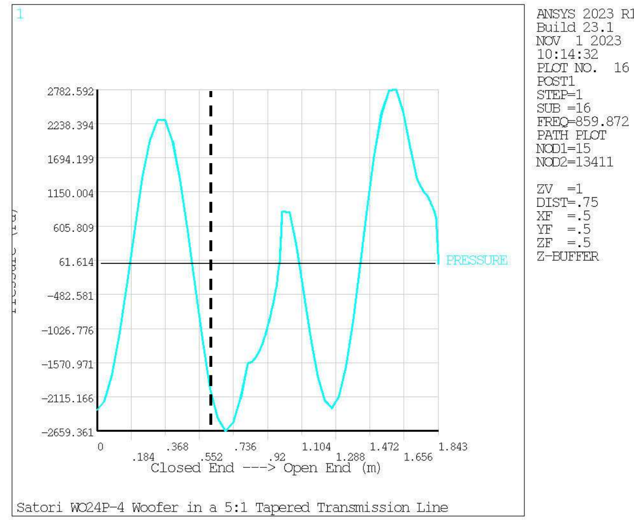


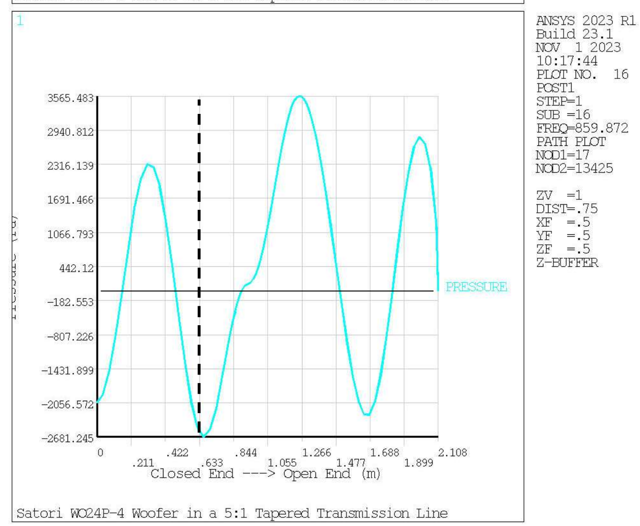




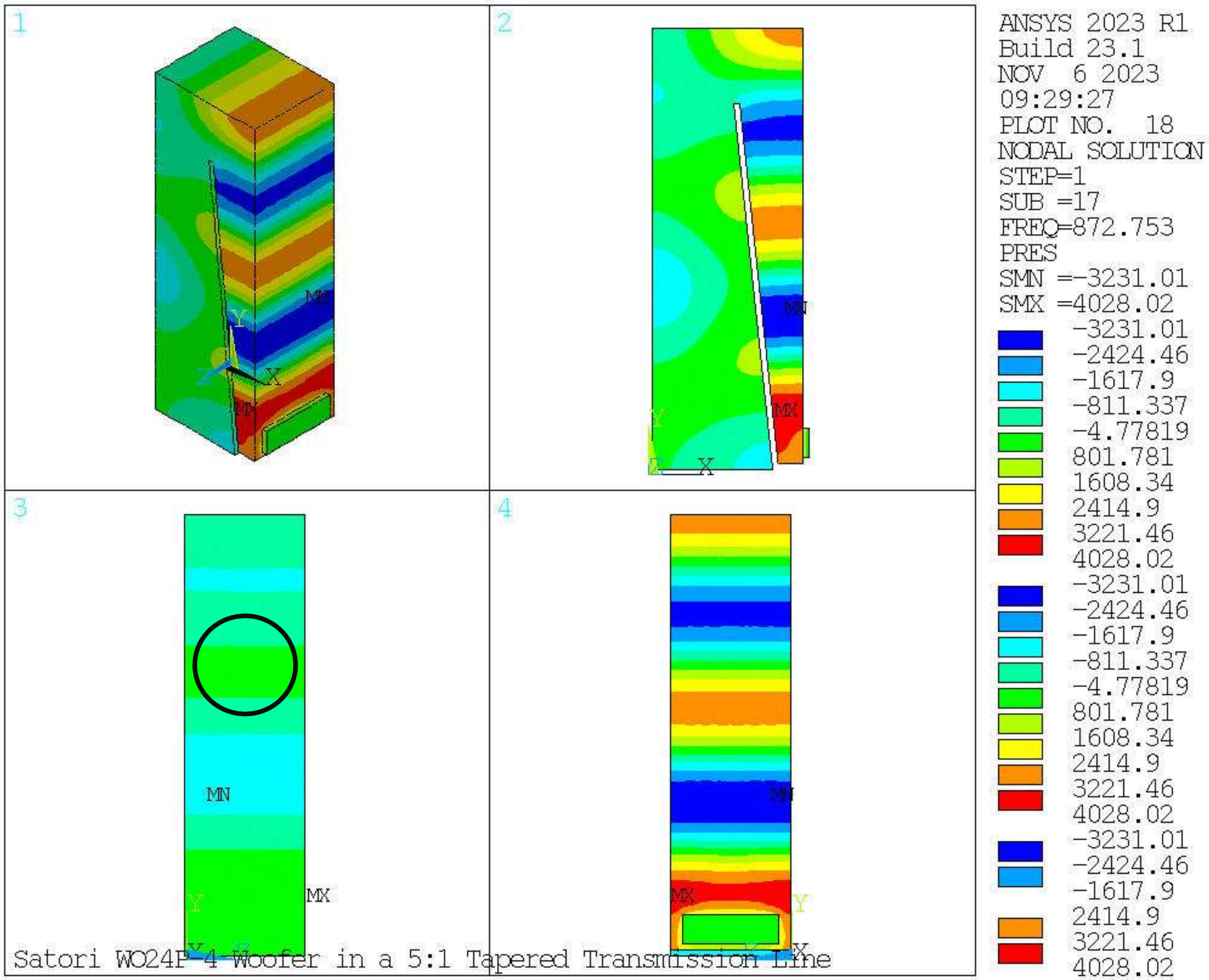
Side to Side – 859.9 Hz

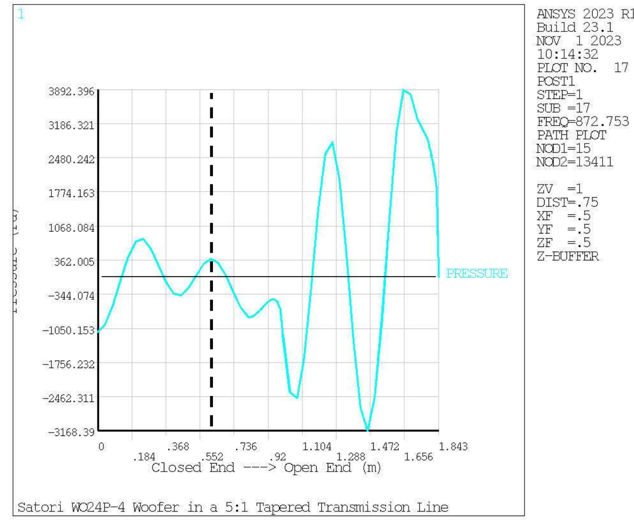


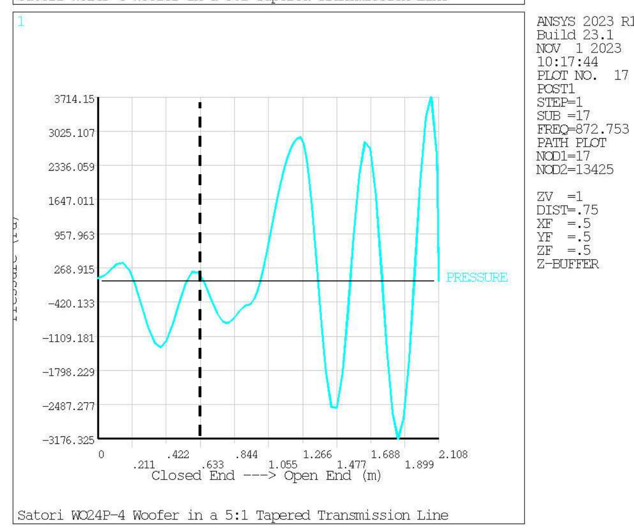




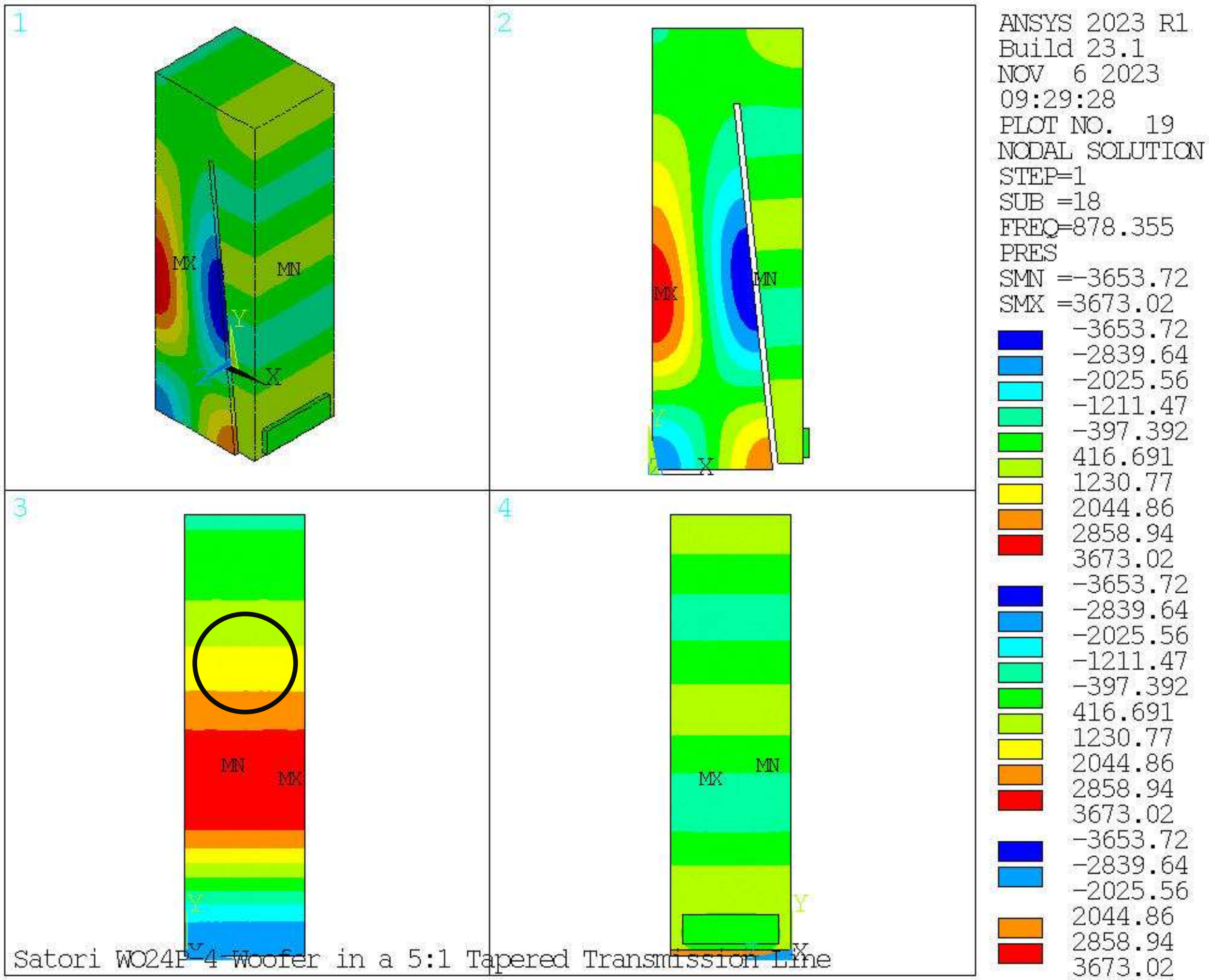
Axial Mode 11 – 872.8 Hz

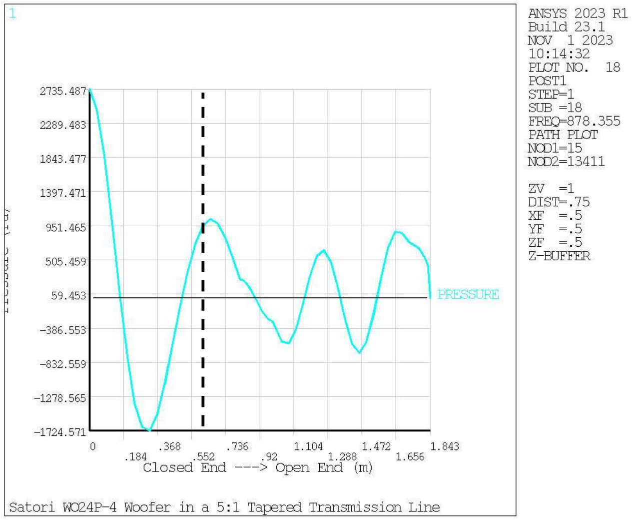


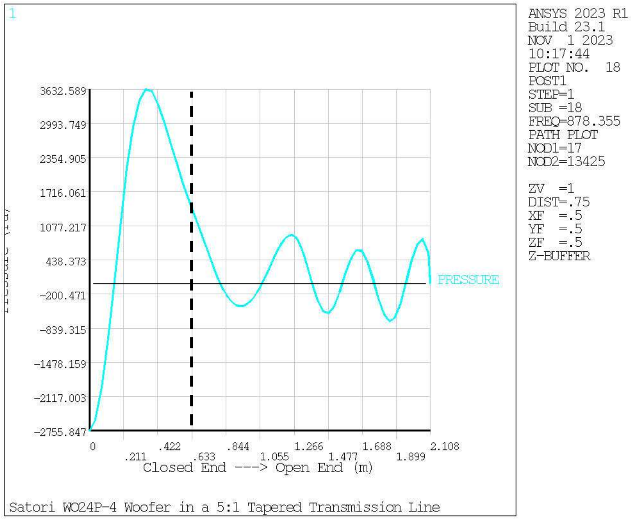




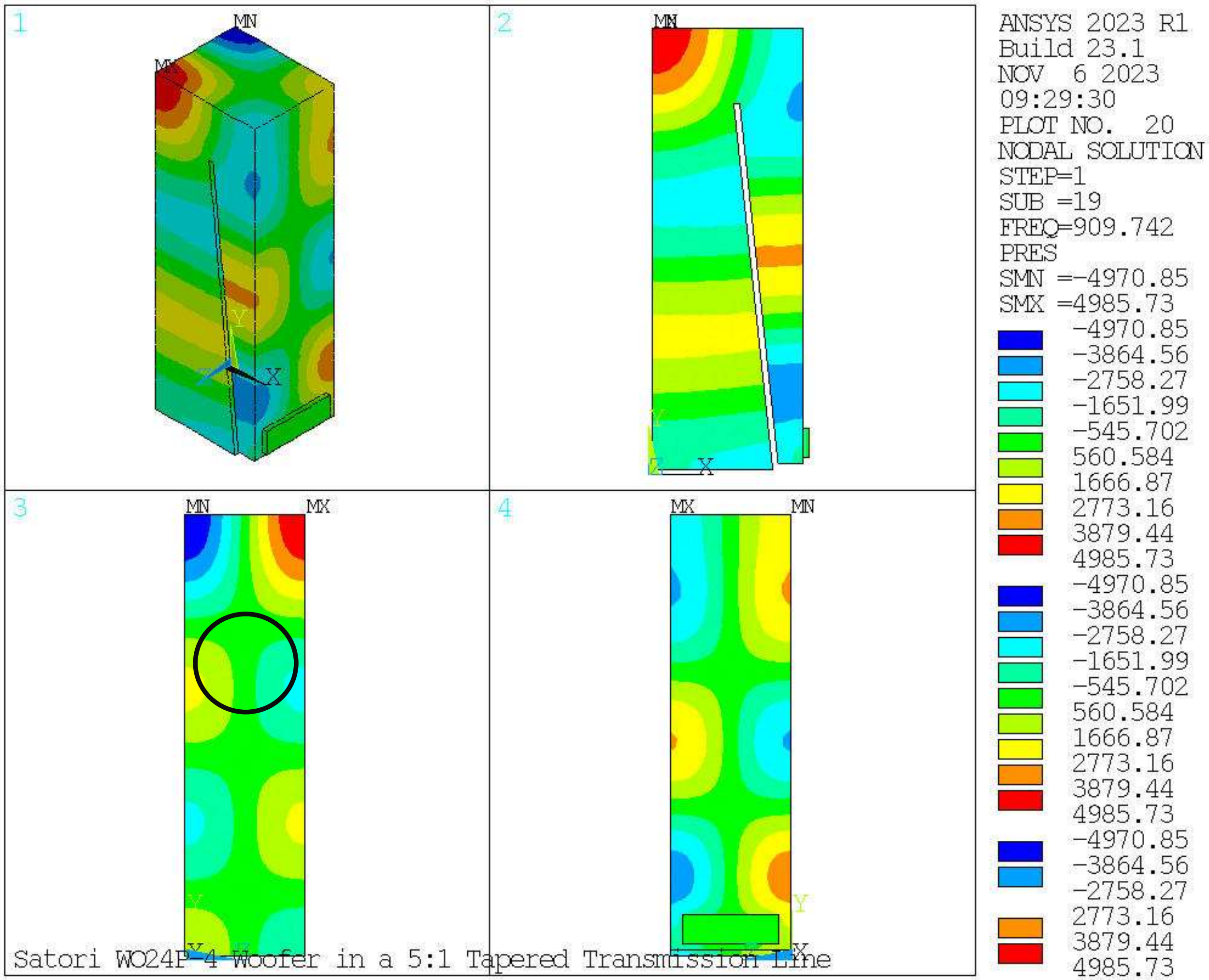
Front to Back – 878.4 Hz

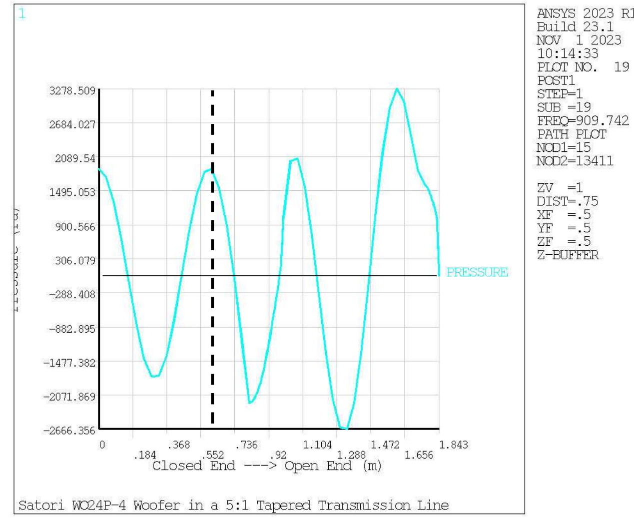


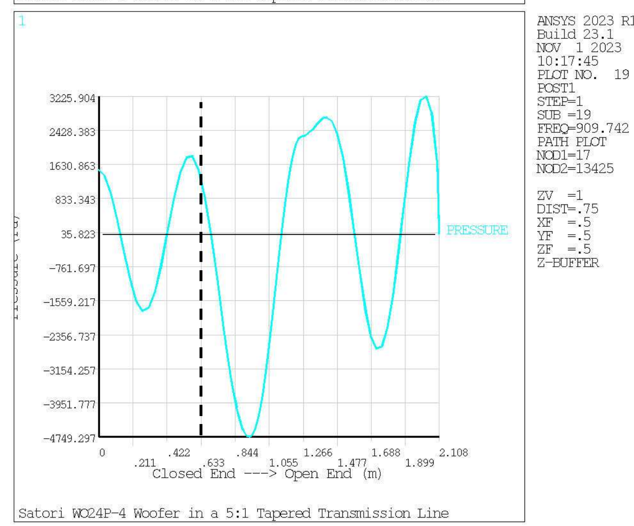




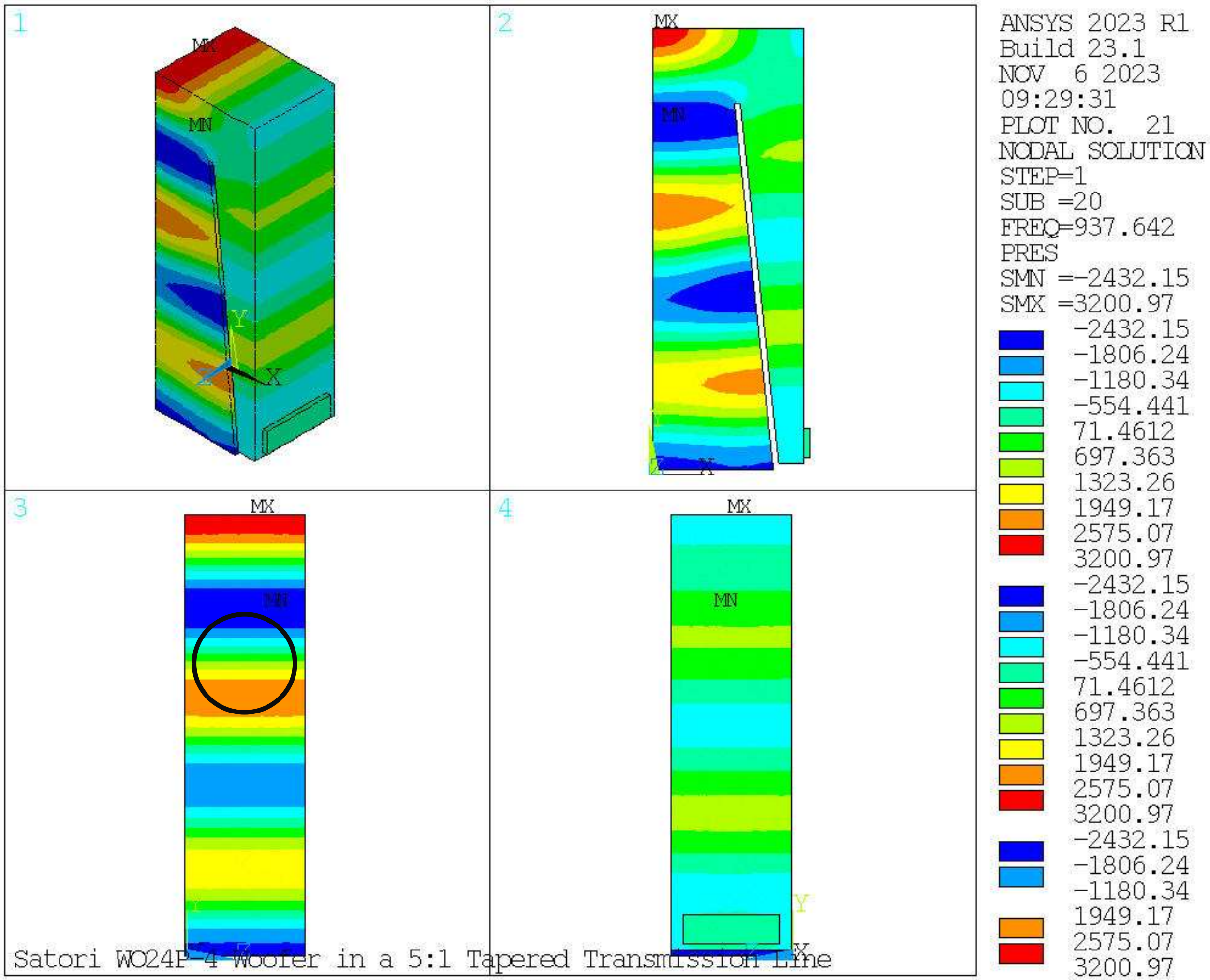
Side to Side – 909.7 Hz

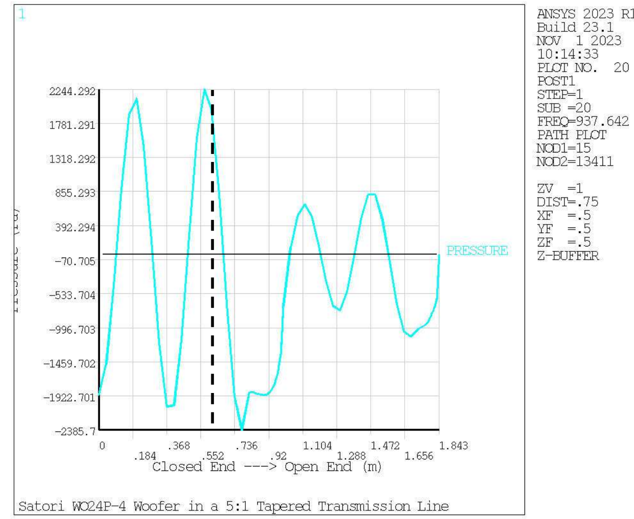


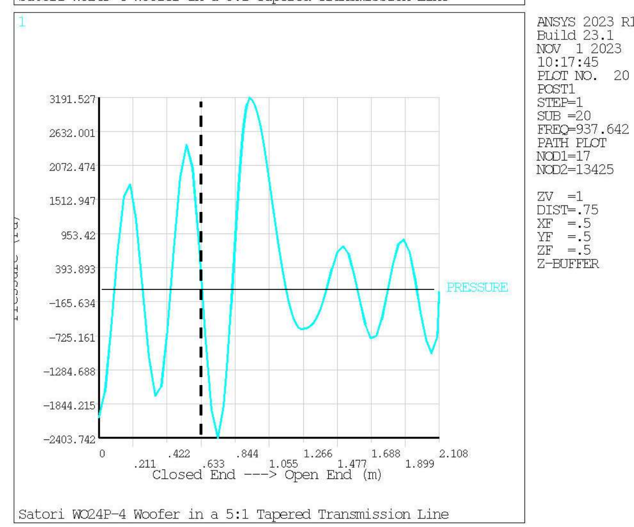




Axial Mode 12 – 937.6 Hz







Attachment 2 : Air Displacement Inside the TL Enclosure

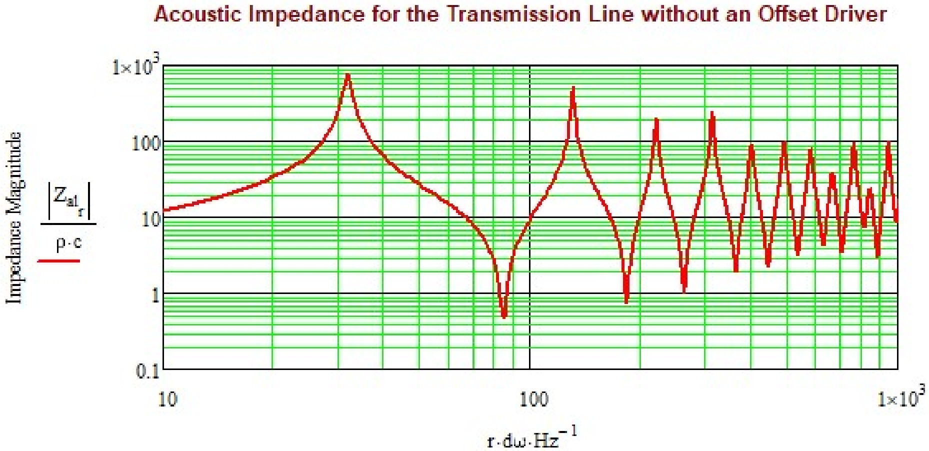
The 1D MathCad model was used to calculate the magnitude of the oscillating air motion inside the Satori TL enclosure.

- The woofer was offset from the closed end. The amount of excitation to each standing wave resonance will be different depending on the axial mode shape.
- No fiber stuffing was used in the simulation and an acoustic BC at the open end was applied minimizing any damping of the resonances. A very small loss is included along the length to maintain solution stability, this was empirically derived for the first MathCad TL models over 20 years ago.
- The responses represent an undamped highly resonant enclosure, a configuration that would never be considered high fidelity.

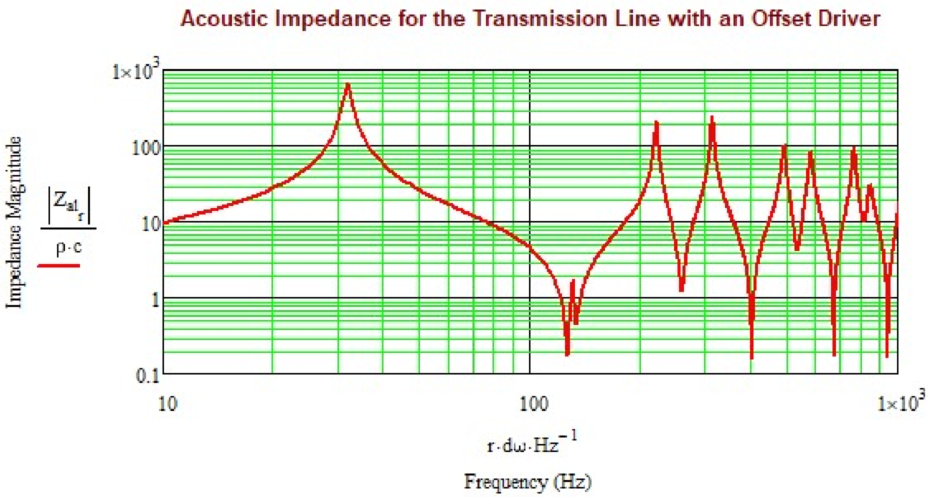
These results should be considered worst case. For a TL with an offset woofer, fiber stuffing, and an acoustic BC at the open end the response will be much more controlled.

These results are directly comparable with the calculated and measured terminus SPL response curves on Slide 13.

Acoustic Impedances of the Empty TL Model



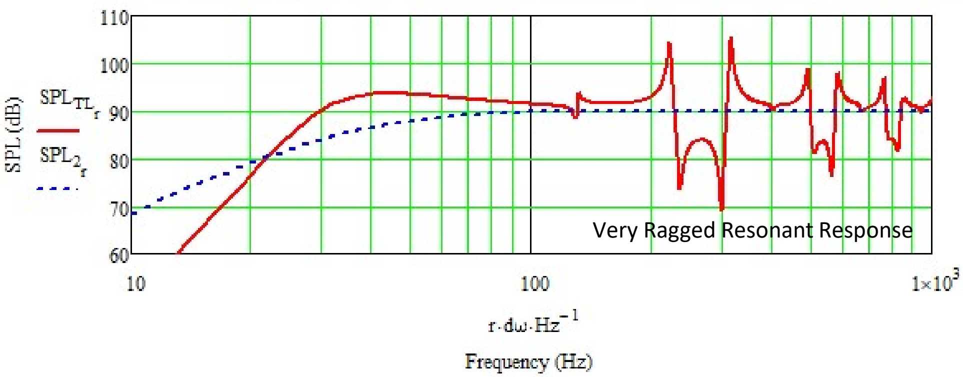
Without an offset driver, the TL's acoustic impedance peaks at every standing wave resonance. The deep nulls between the peaks result from the 180-degree phase difference between the mode directly above and below the null. Every time you pass through a resonance peak the acoustic impedance's phase swings from +90 degrees to -90 degrees.



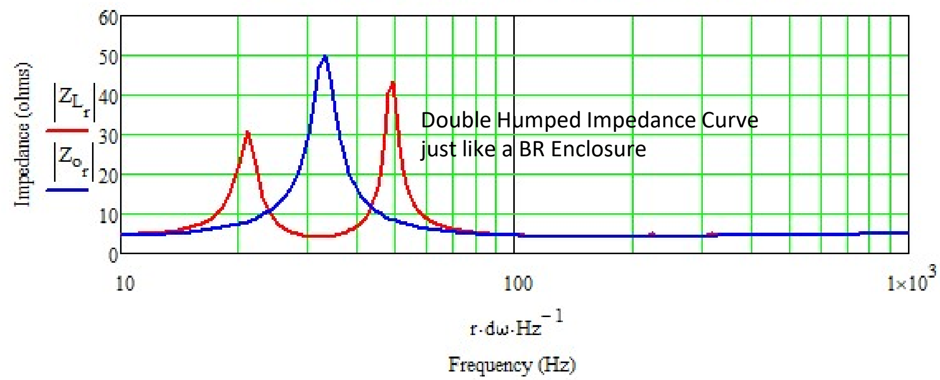
When the driver is offset, the intent is to remove the 3/4, 9/4, 15/4, and 21/4 standing waves. The acoustic impedance at left shows this was successful for the 9/4, 15/4, and 21/4 modes since a peak in the upper plot has been replaced by a deeper null in the lower plot. Unfortunately, the offset was not perfectly placed so the 3/4 mode can still be seen as a peak rising out of the slightly misaligned null.

Acoustic Responses of the Empty TL – 2 Pi Space

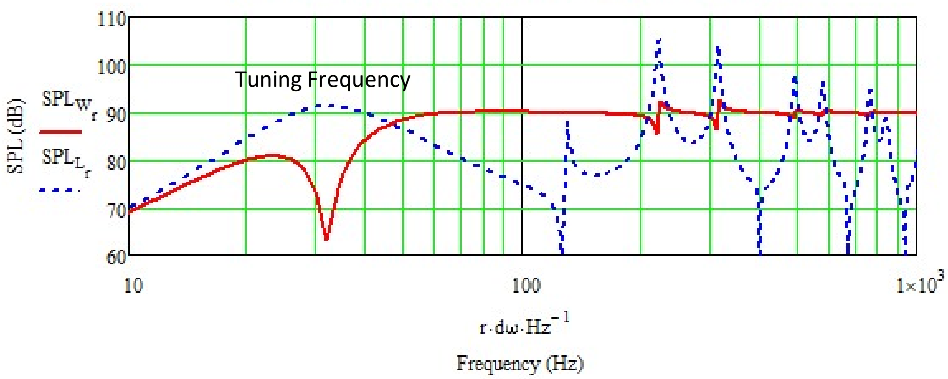
Transmission Line System and Woofer Infinite Baffle Sound Pressure Level Responses



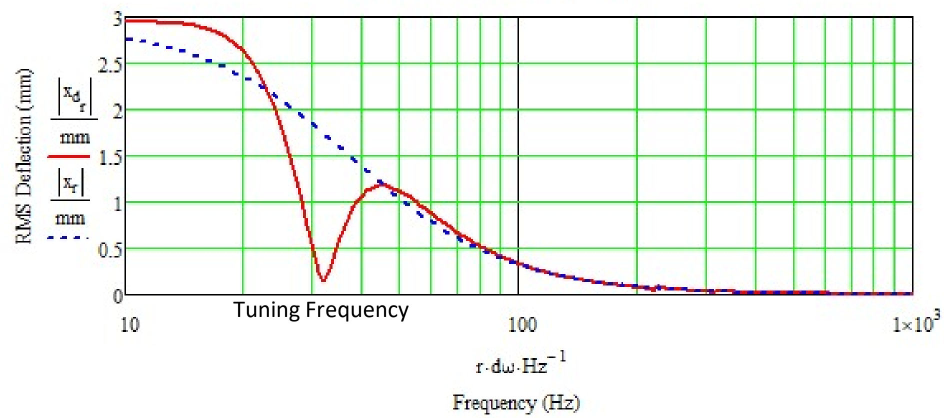
Transmission Line System and Infinite Baffle Impedance

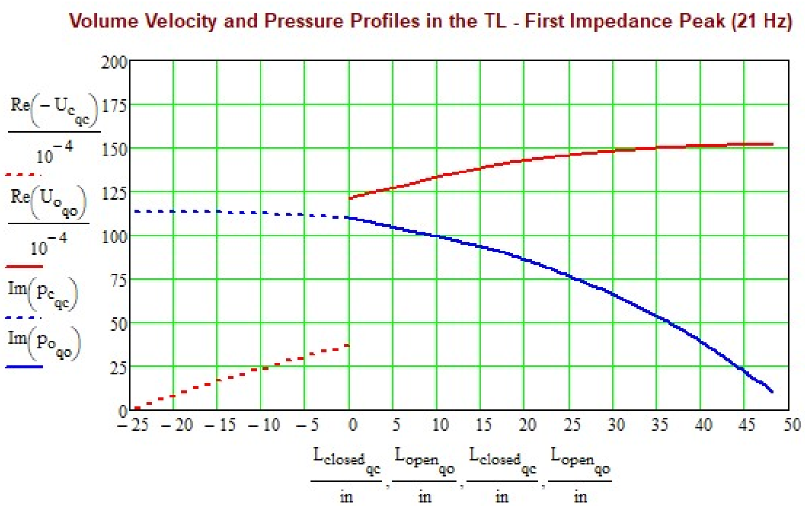


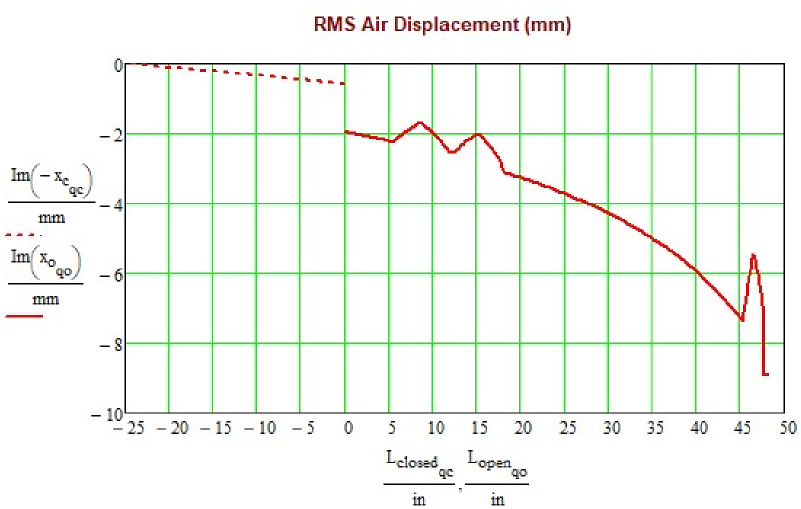
Woofer and Terminus Sound Pressure Level Responses



Woofer RMS Displacement







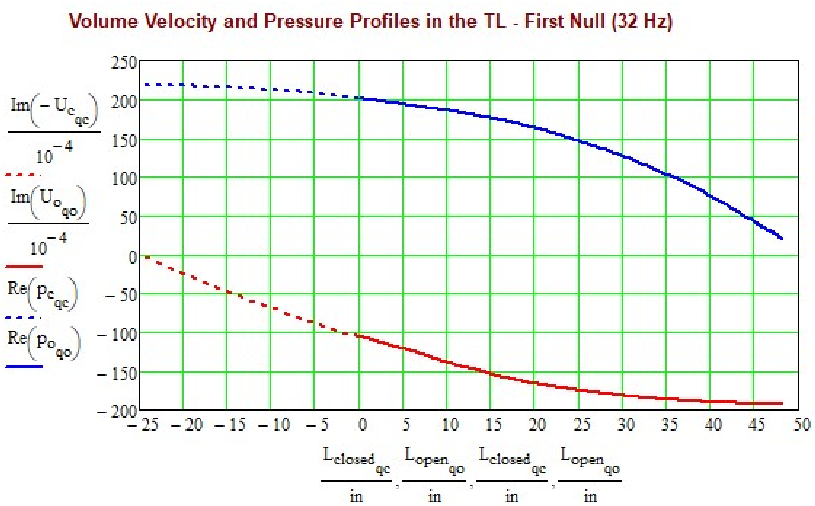
Mode 1 - First Electrical Impedance Peak

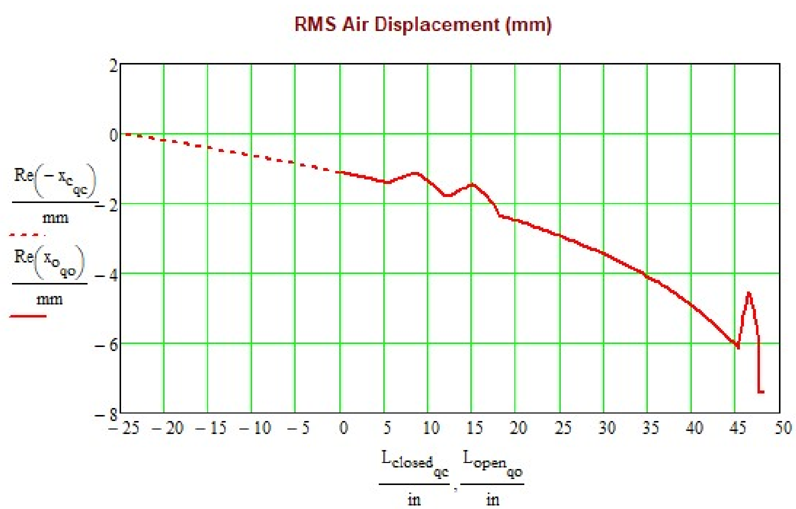
Dashed curves are for the driver to the closed end, solid curves are for the driver to the open end. The driver is located at zero on the x-axis.

Pressure profile is continuous, maximum at the closed end and minimum at the terminus.

The Step change in the plotted volume velocity and displacement curves is due to the woofer's motion, summing the three motions (multiplied by the associated areas) with appropriate sign convention nets to zero.

Maximum oscillating displacement is ~8.5 mm at the terminus, ~3.0 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.



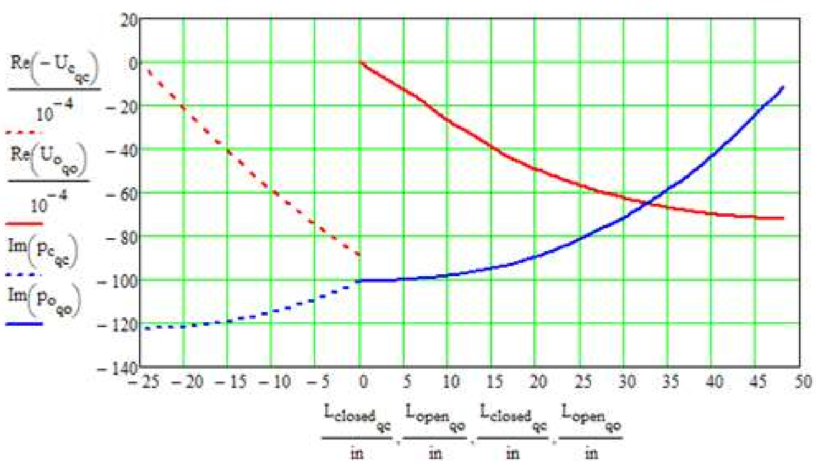


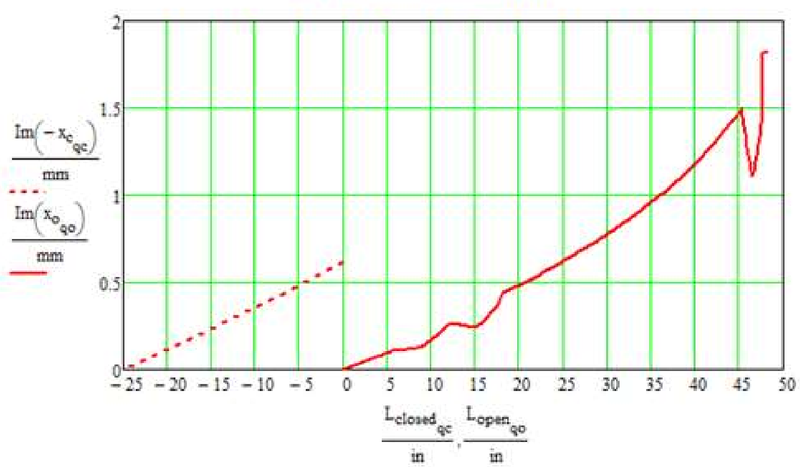
First Impedance Null – 1/4 Wave Response

Pressure profile is continuous, maximum at the closed end and minimum at the terminus. Like a BR, this response produces the TL's bass output.

No step change in the plotted volume velocity and displacement curves due to the woofer's motion being significantly attenuated, like a bass reflex enclosure's behavior at the tuning frequency. This is seen in the driver displacement plot as a deep null.

Maximum oscillating displacement is ~7.5 mm at the terminus, ~2.0 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space. Even though the displacement looks significant, the air velocity is below the limit used in BR design to avoid chuffing or other unintended port noises.





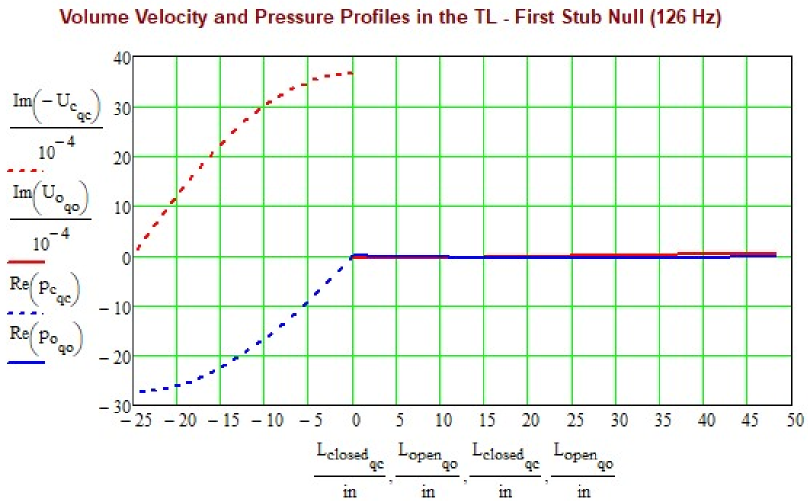
Mode 2 - Second Electrical Impedance Peak

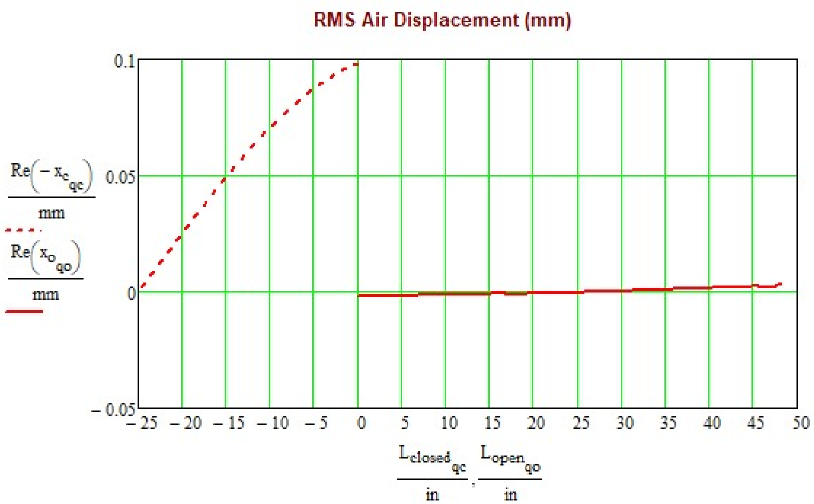
Pressure profile is continuous, still maximum at the closed end and minimum at the terminus.

The step change in the plotted volume velocity and displacement curves is due to the woofer's motion, summing the three motions (multiplied by the associated areas) with appropriate sign convention nets to zero.

Maximum oscillating displacement is ~1.75 mm at the terminus, ~0.25 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.

Notice in the series of plots that the oscillating air displacement is decreasing with increasing frequency.





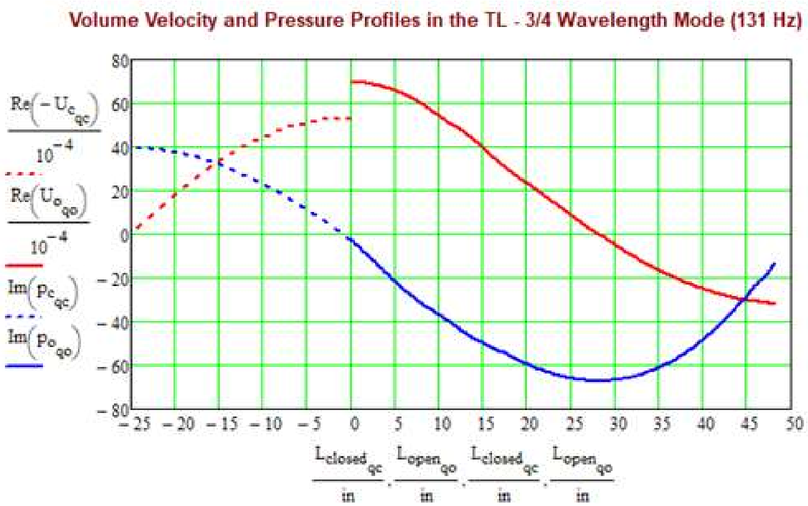
First Acoustic Null – 1/4 Wave to Closed End

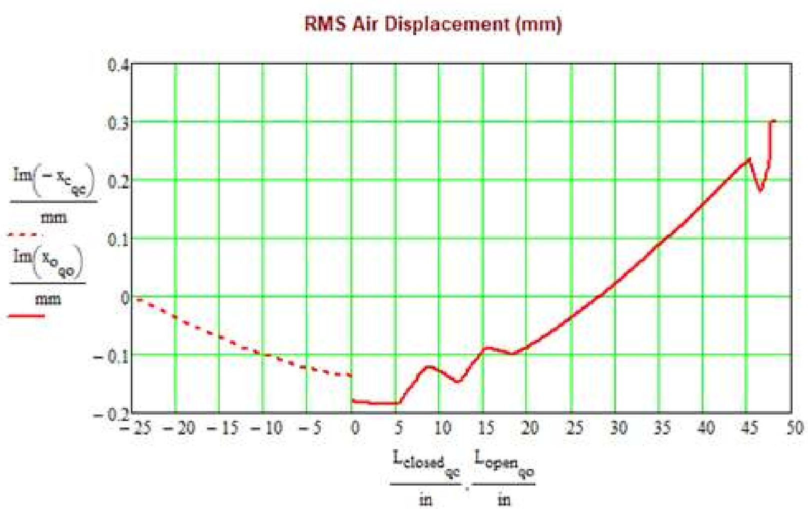
Pressure profile is maximum at the closed end and minimum at the woofer, minimum for the entire open end to the terminus.

All the response is directed towards the closed end. The acoustic impedance of the closed end, the stub, is essentially zero so it acoustically shorts the open end of the TL

Maximum oscillating displacement is ~0 mm at the terminus, ~0 mm at the 180-degree fold, and ~0.1 mm at the woofer position for the TL producing 90 dB at 1 meter into 2 Pi space.

This is a form of the 3/4 wave resonance and mode shape of the speaker system.





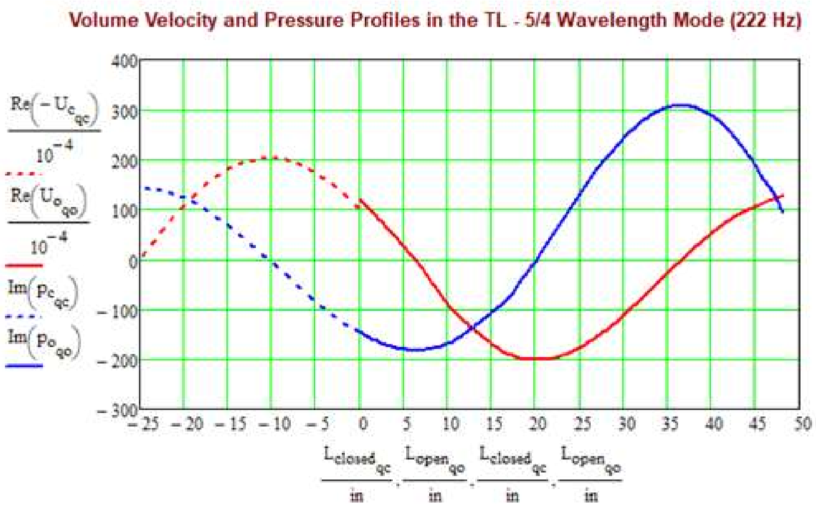
Mode 3 – 3/4 Wave Response

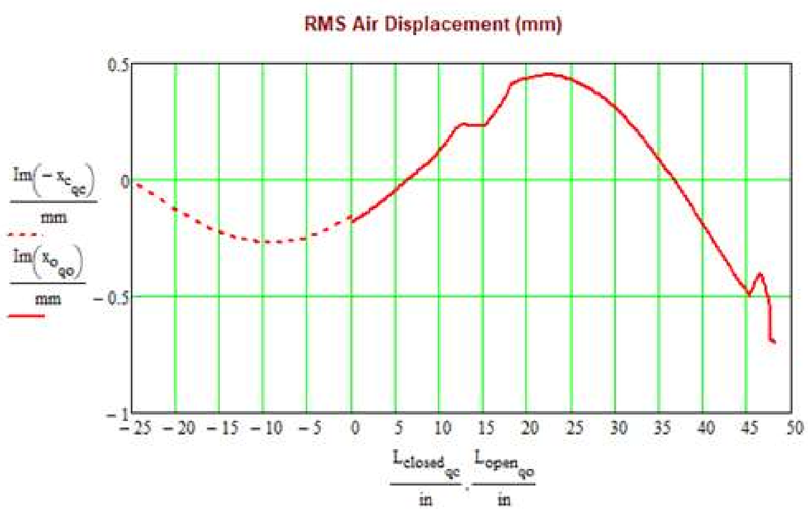
Pressure profile is continuous, maximum at approximately 3/4 of the TL length. Mode is not strongly excited; pressure magnitude is lower compared to quarter wave resonances above and below this mode.

Smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone motion.

Maximum oscillating displacement is ~0.3 mm at the terminus, ~0.2 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.

Again, the oscillating air displacement is still decreasing with increasing frequency.



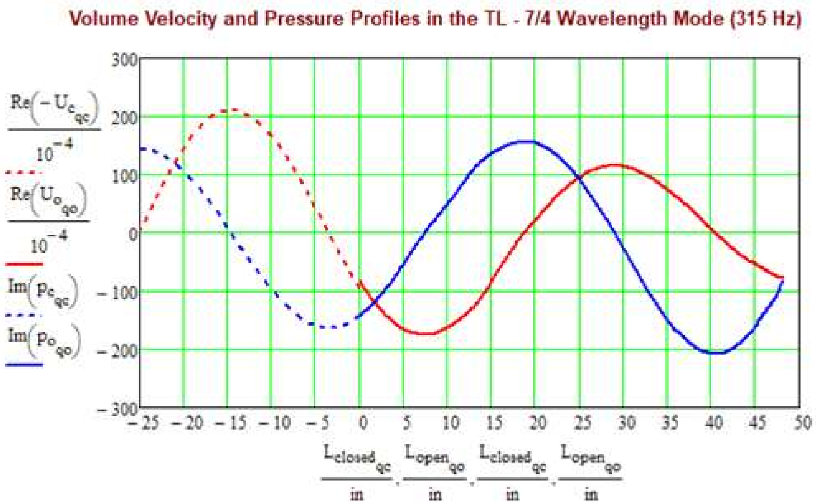


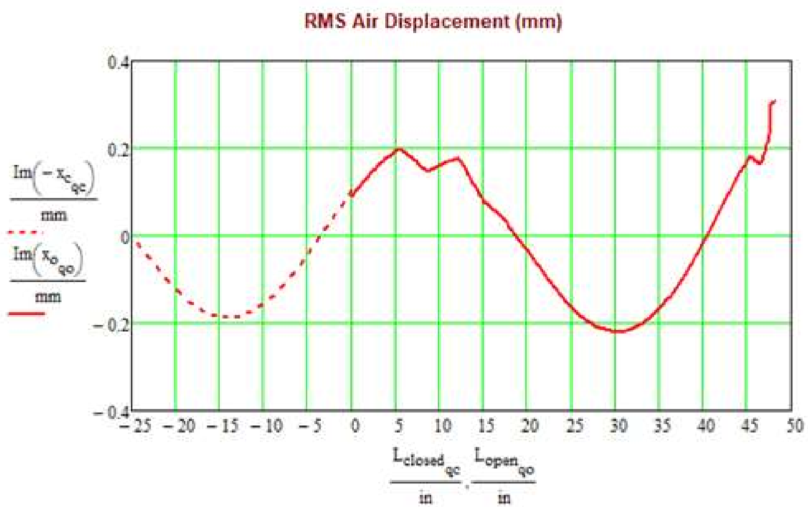
Mode 4 – 5/4 Wave Response

Pressure profile is continuous, maximum at approximately one wavelength along the TL length. Mode is strongly excited; pressure magnitude is typical of the quarter wave resonances below this mode.

Very smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone motion. The standing wave is near a peak pressure behind the woofer cone attenuating its motion.

Maximum oscillating displacement is ~0.75 mm at the terminus, ~0.4 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.



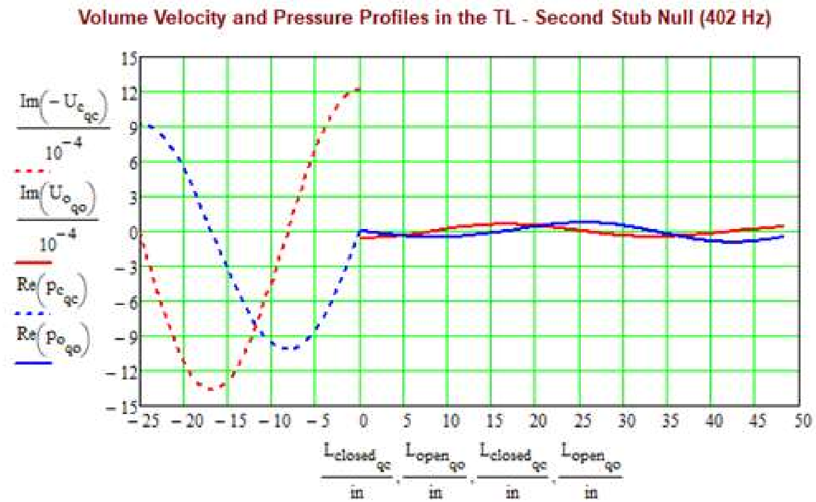


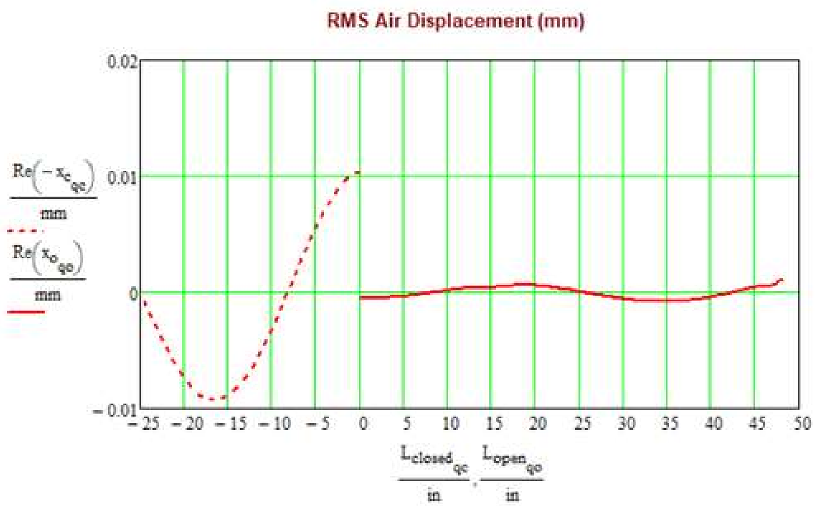
Mode 5 – 7/4 Wave Response

Pressure profile is continuous, maximum at approximately 1.5 wavelengths along the TL length. Mode is strongly excited; pressure magnitude is typical of the quarter wave resonances below this mode.

Very smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone motion. The standing wave is near a peak pressure behind the woofer cone attenuating its motion.

Maximum oscillating displacement is ~0.3 mm at the terminus, ~0.2 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.





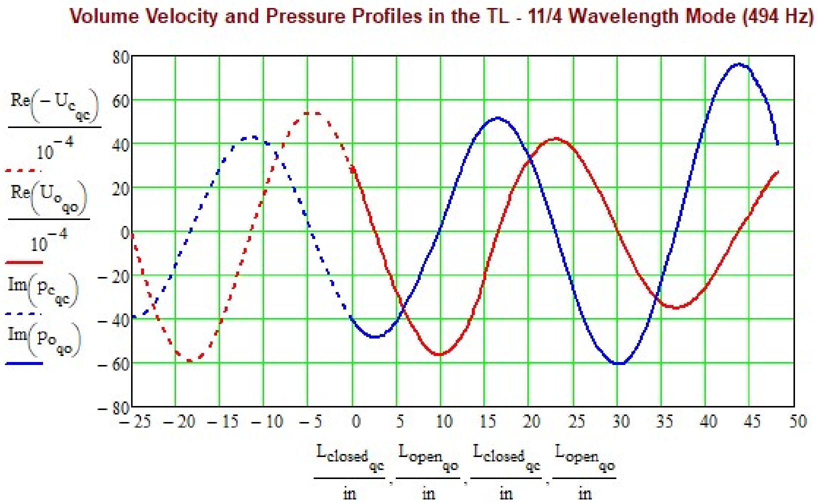
Second Acoustic Null – 3/4 Wave to Closed End

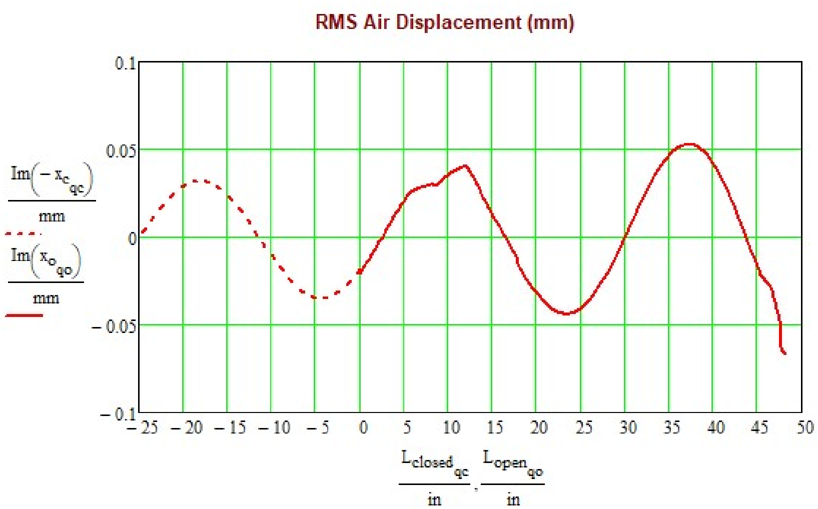
Pressure profile maximum at the closed end and minimum at the woofer, minimum for the entire open end to the terminus.

All the response is directed towards the closed end. The acoustic impedance of the closed end, the stub, is essentially zero so it acoustically shorts the open end of the TL

Maximum oscillating displacement is ~0 mm at the terminus, ~0 mm at the 180-degree fold, and ~0.01 mm at the woofer position for the TL producing 90 dB at 1 meter into 2 Pi space.

This is a form of the 9/4 wave resonance and mode shape of the speaker system.



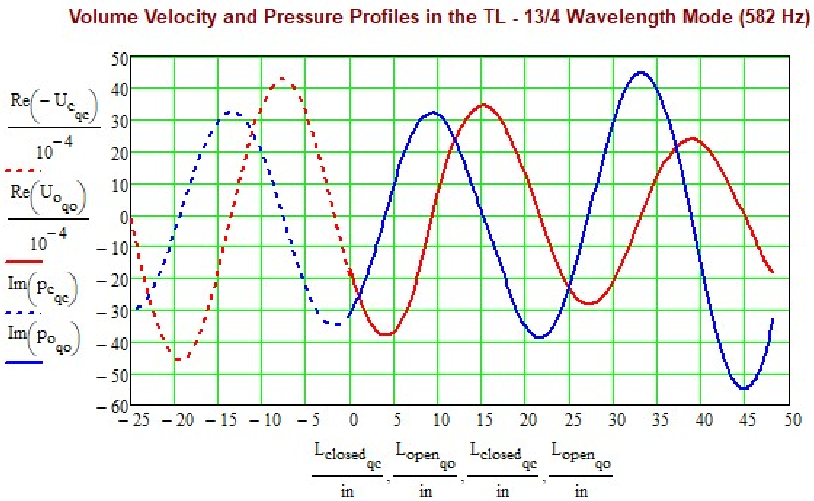


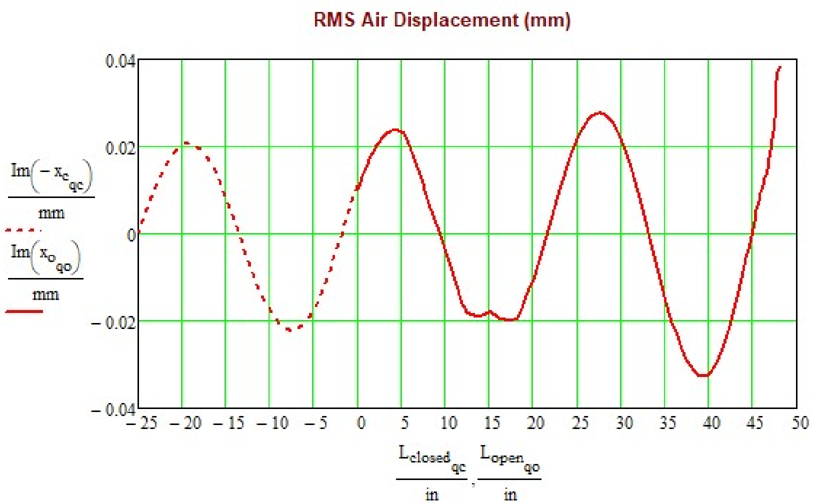
Mode 7 – 11/4 Wave Response

Pressure profile is continuous, maximum at approximately 2.5 wavelengths along the TL length. Mode is strongly excited; pressure magnitude is decreasing compared to the quarter wave resonances below this mode.

Very smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone motion. The standing wave is halfway to a peak pressure behind the woofer cone attenuating its motion.

Maximum oscillating displacement is ~0.07 mm at the terminus, ~0.04 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.



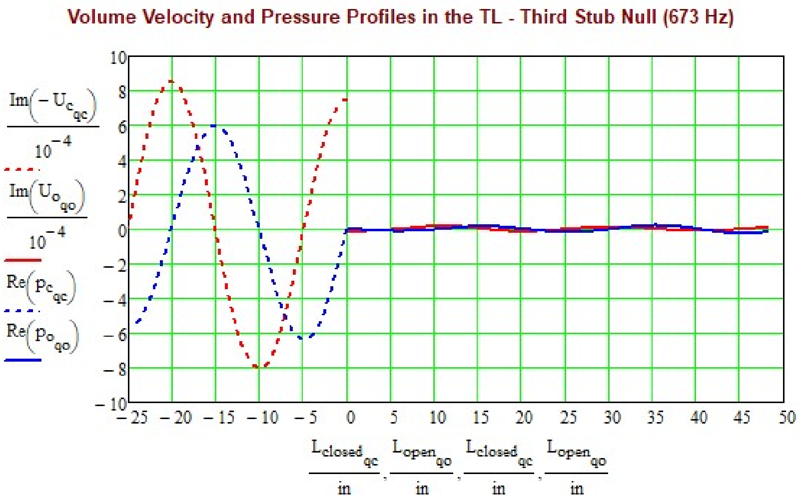


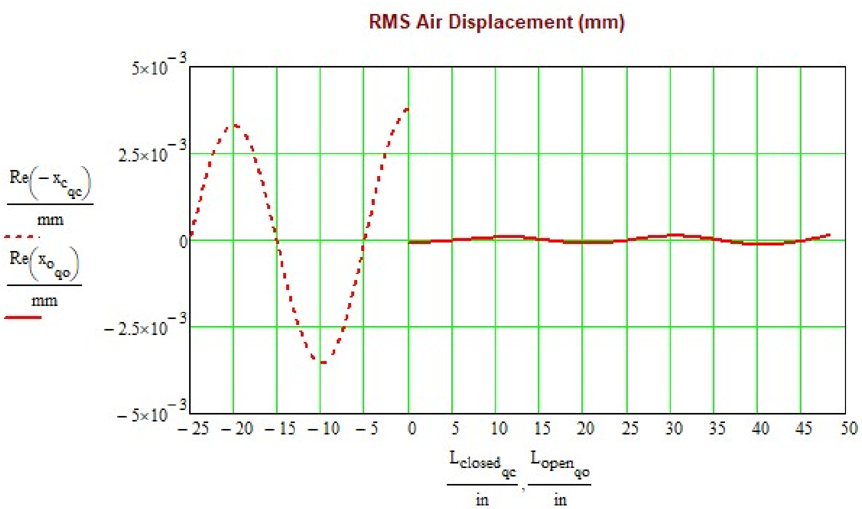
Mode 8 – 13/4 Wave Response

Pressure profile is continuous, maximum at approximately 3 wavelengths along the TL length. Mode is strongly excited; pressure magnitude is decreasing compared to the quarter wave resonances below this mode.

Very smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone. The standing wave is halfway to a peak pressure behind the woofer cone attenuating its motion.

Maximum oscillating displacement is ~0.04 mm at the terminus, ~0.02 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.





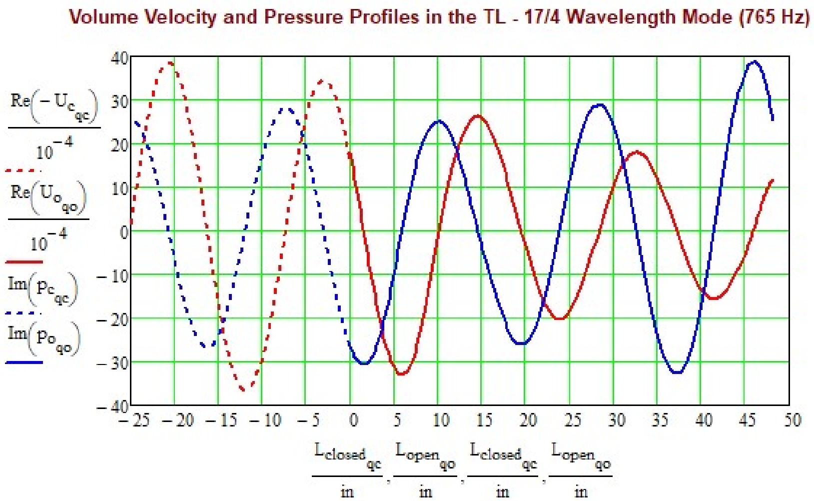
Third Acoustic Null – 5/4 Wave to Closed End

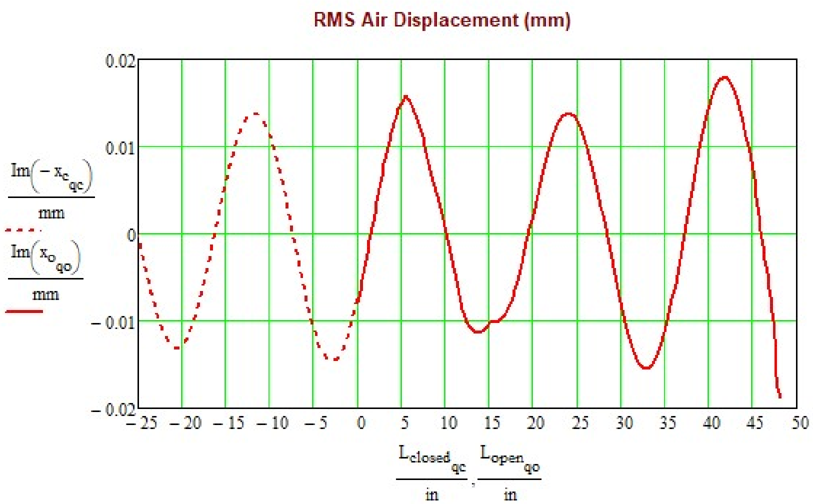
Pressure profile maximum at the closed end and minimum at the woofer, minimum for the entire open end to the terminus.

All the response is directed towards the closed end. The acoustic impedance of the closed end, the stub, is essentially zero so it acoustically shorts the open end of the TL

Maximum oscillating displacement is ~0 mm at the terminus, ~0 mm at the 180-degree fold, and ~0.00375 mm at the woofer position for the TL producing 90 dB at 1 meter into 2 Pi space.

This is a form of the 15/4 wave resonance and mode shape of the speaker system.



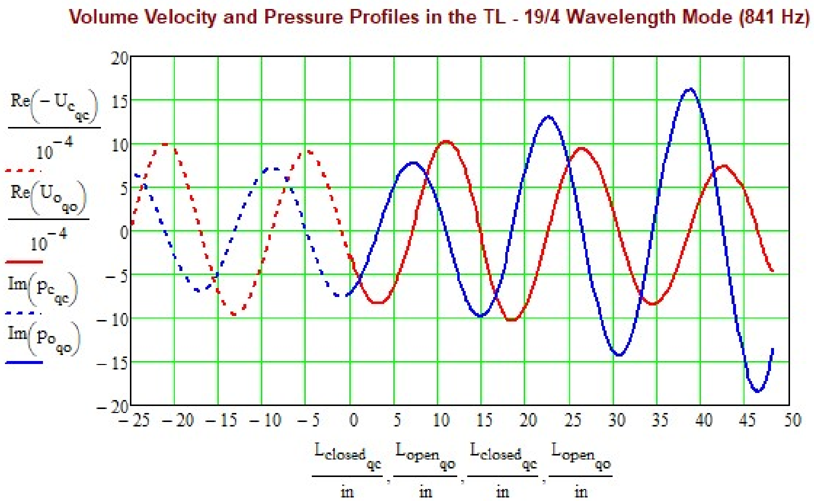


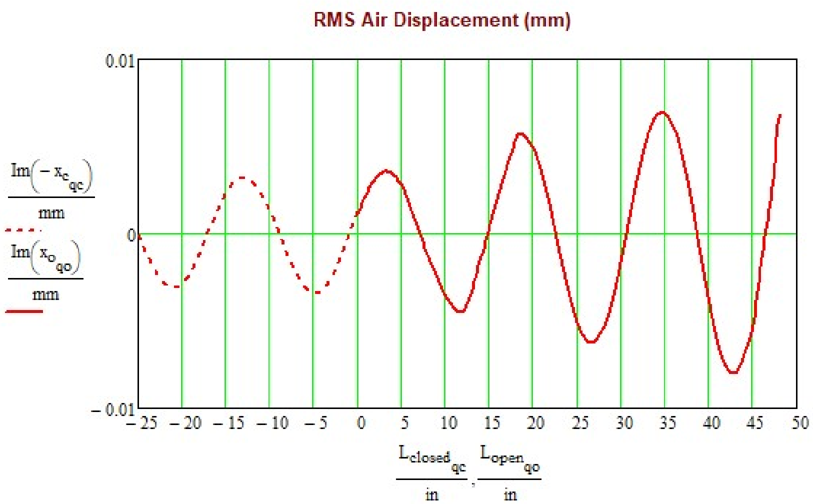
Mode 10 – 17/4 Wave Response

Pressure profile is continuous, maximum at approximately 4 wavelengths along the TL length. Mode is strongly excited; pressure magnitude is decreasing compared to the quarter wave resonances below this mode.

Very smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone motion. The standing wave is halfway to a peak pressure behind the woofer cone attenuating its motion.

Maximum oscillating displacement is ~0.02 mm at the terminus, ~0.01 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.



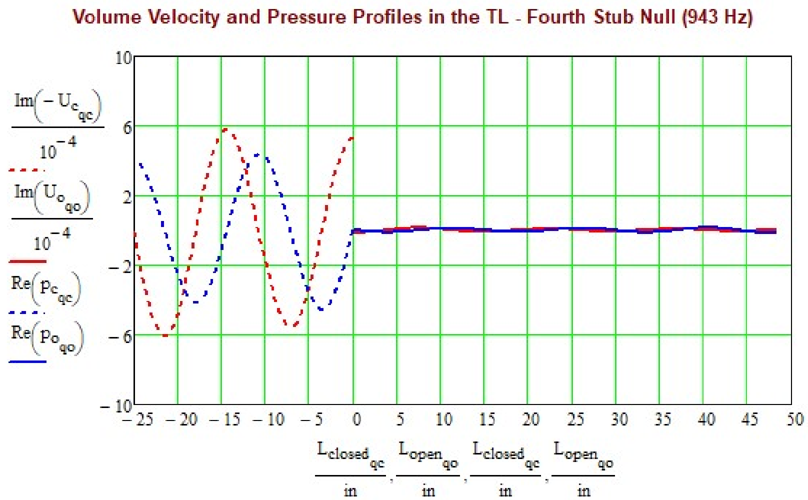


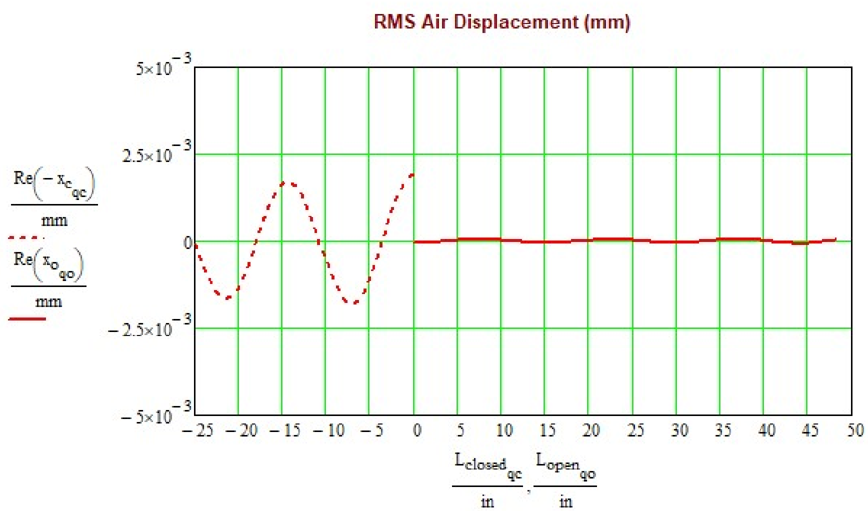
Mode 11 – 19/4 Wave Response

Pressure profile is continuous, maximum at approximately 4.5 wavelengths along the TL length. Mode is strongly excited; pressure magnitude is decreasing compared to the quarter wave resonances below this mode.

Very smaller step change in the plotted volume velocity and displacement curves due to the woofer's cone motion. The standing wave is halfway to a peak pressure behind the woofer cone attenuating its motion.

Maximum oscillating displacement is ~0.007 mm at the terminus, ~0.0 mm at the 180-degree fold, for the TL producing 90 dB at 1 meter into 2 Pi space.





Fourth Acoustic Null – 7/4 Wave to Closed End

Pressure profile maximum at the closed end and minimum at the woofer, minimum for the entire open end to the terminus.

All the response is directed towards the closed end. The acoustic impedance of the closed end, the stub, is essentially zero so it acoustically shorts the open end of the TL

Maximum oscillating displacement is ~0 mm at the terminus, ~0 mm at the 180-degree fold, and ~0.002 mm at the woofer position for the TL producing 90 dB at 1 meter into 2 Pi space.

This is a form of the 21/4 wave resonance and mode shape of the speaker system.