Using Modal Analysis to Understand Transmission Line Speaker Enclosure Response Part 3 – Folded Geometry Behavior

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Introduction

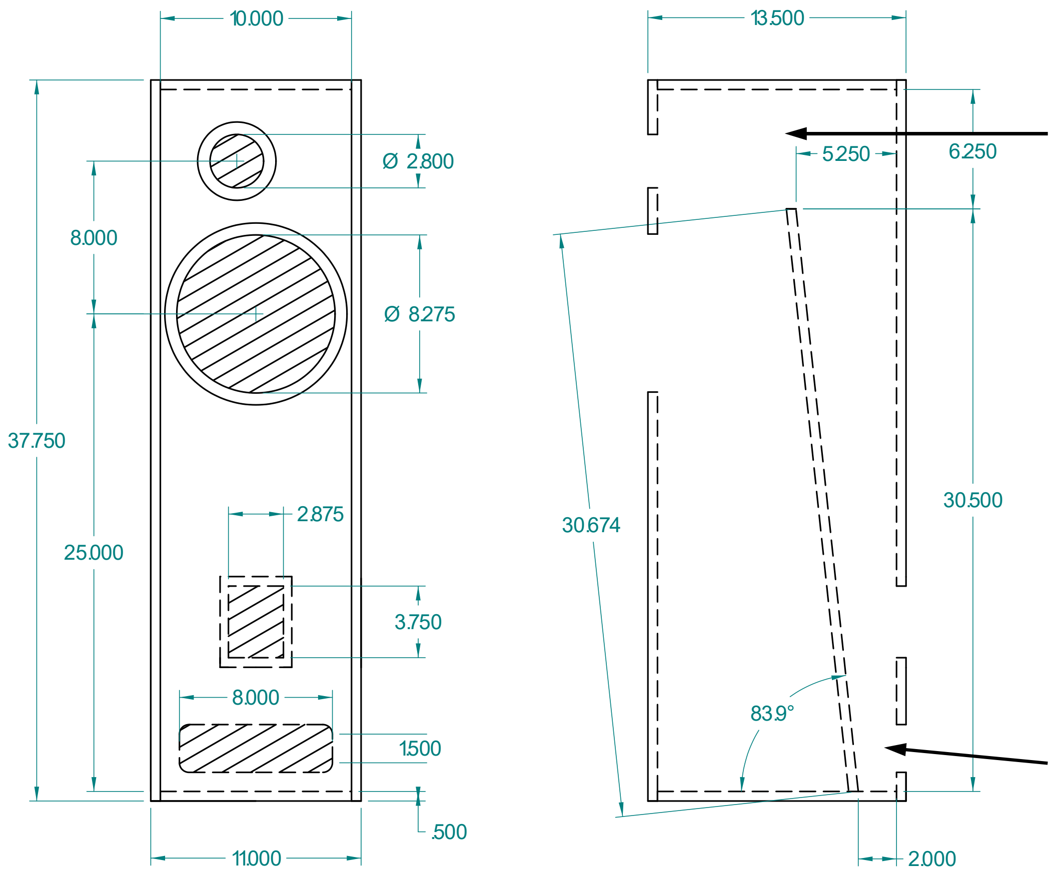
The long axial length required in TL designs almost always result in a folding of the path to make it fit within a conventional rectangular shaped enclosure. The behavior of the folded geometry used in TL speaker enclosures has almost as many rules of thumb and postulated acoustic behaviors as the fiber stuffing or foam lining did before modern simulation software became available. There are many proposals for how to model the acoustic path as it navigates through a series of folds/bends in a TL enclosure and what to assume as the equivalent length and cross-sectional areas to accurately simulate this convoluted path.

After reviewing the simulation and measurement results from my recent Satori TL design and build, one of the areas identified for subsequent study was the behavior and impact of the single 180-degree fold at the top of the enclosure and the final 90-degree bend at the bottom just before the terminus. I believe that the outcome of this study has generated a more accurate method for modeling these geometric discontinuities, the method and results will be presented in the following slides

The Satori TL Speaker Design

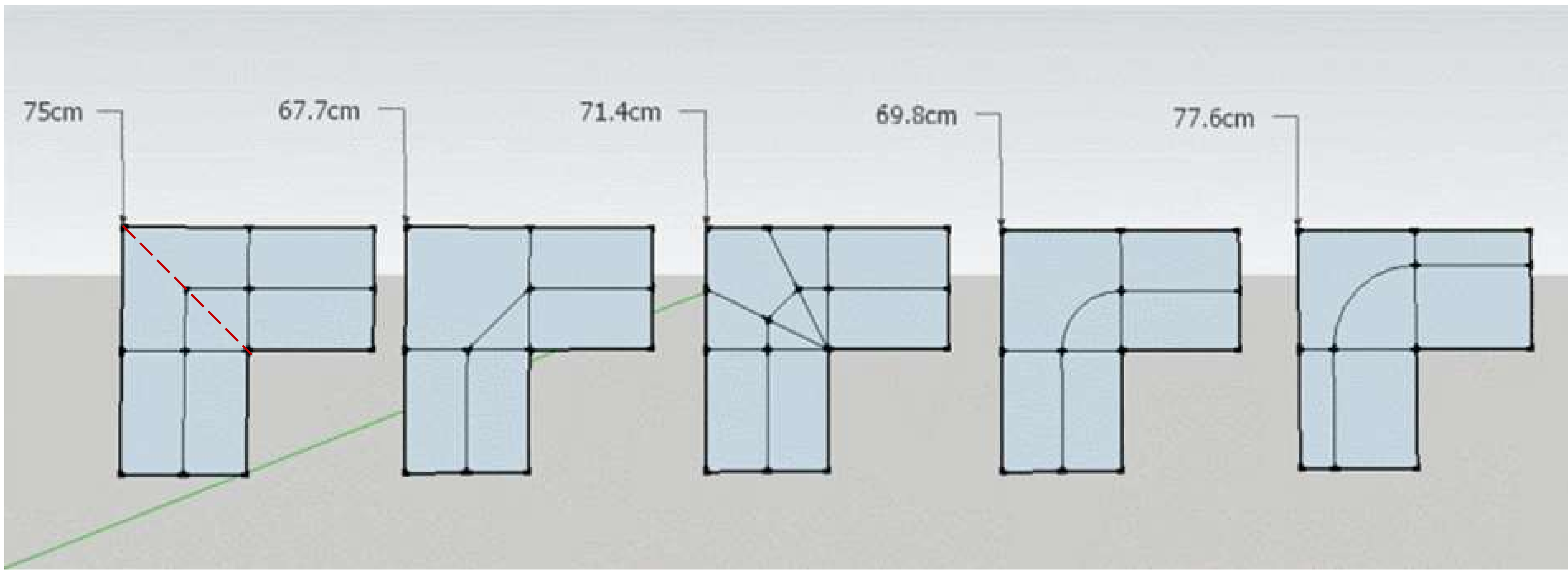
The recently completed Satori TL was used as a test bed for comparing the simulated and measured acoustic and electrical properties. Measurements of the electrical impedance and near and far field SPL's of the woofer and terminus were taken for an empty TL, a fiber stuffed TL, and an egg crate acoustic foam lined TL. Of particular interest, the differences between the calculated and measured near field terminus SPLs has facilitated the study of the air motions within the TL enclosure including the impact of modeling the fold and bend in the path geometry.

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



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

Current Methods Used by DIYers to Represent a Fold in a TL or Horn Geometry



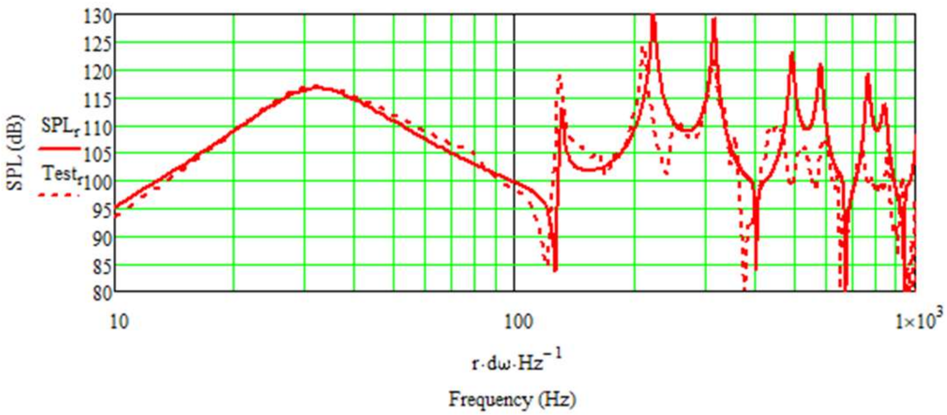
I lifted this picture from the Internet. I do not know its origin, but it is referenced on many on-line forums and discussion groups. When I model a TL, I use the left-hand method (the centerline method) with the addition of a diagonal (red dashed line) across the corner. Hornresp users tend to favor the middle modeling method (the advanced centerline method).

There are several assumptions that go along with these methods of modeling the folds/bends using 1-dimensional acoustic elements.

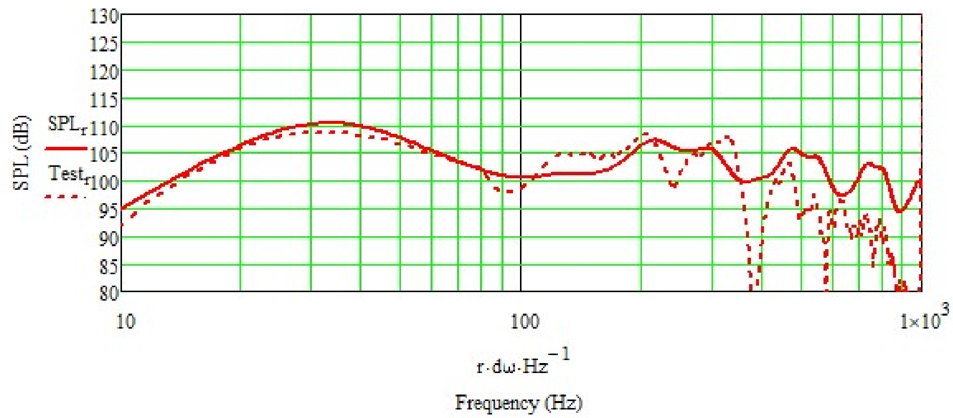
- Each section of the bend geometry is represented by a 1-dimensional acoustic element that has a length and cross-sectional areas defined at each end.
- At each cross-sectional area, the pressure and volume velocity profile is assumed to be constant. Also, the pressure and volume velocity are continuous from element to element.
- Each acoustic element contains equations that relate the pressure and volume velocity at the first cross-sectional area to the second cross-sectional area using a transfer matrix.
- All 1-dimensional simulation codes work fundamentally the same way, analyzing a chain of acoustic elements along the entire length of the TL. The programs see this chain of elements as lying on a straight line, an actual geometric change in direction is not explicitly modeled.
- These 1-dimensional simulations codes include HornResp, LATL, Augspurger's TL code, SPICYTL, as well as my own MathCad worksheets.

Terminus Calculated and Measured SPL Responses for the Satori Transmission Line

Empty TL



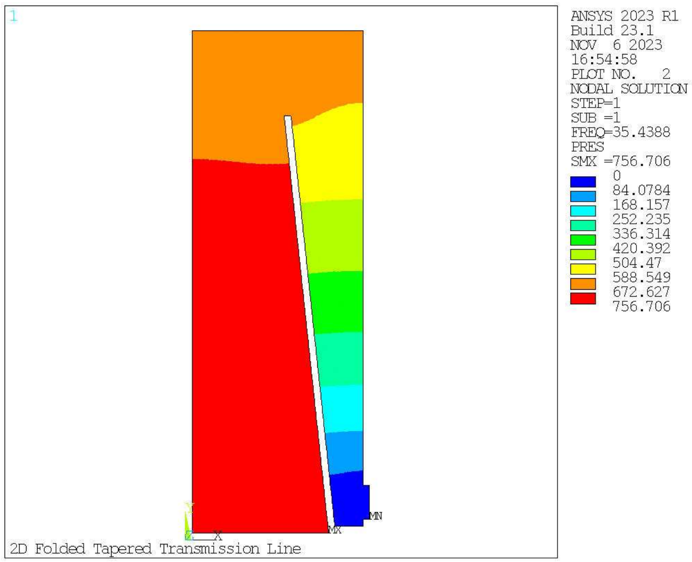
Fiber Stuffed TL

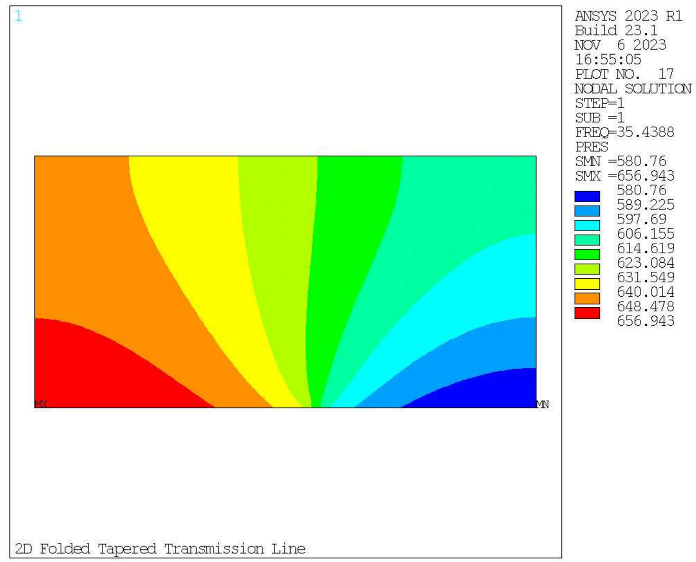


The two plots shown above contain the calculated (solid red curve) and measured (dashed red curve) terminus near field SPL responses. The calculated results use the centerline model to represent the 180-degree fold and 90-degree bend.

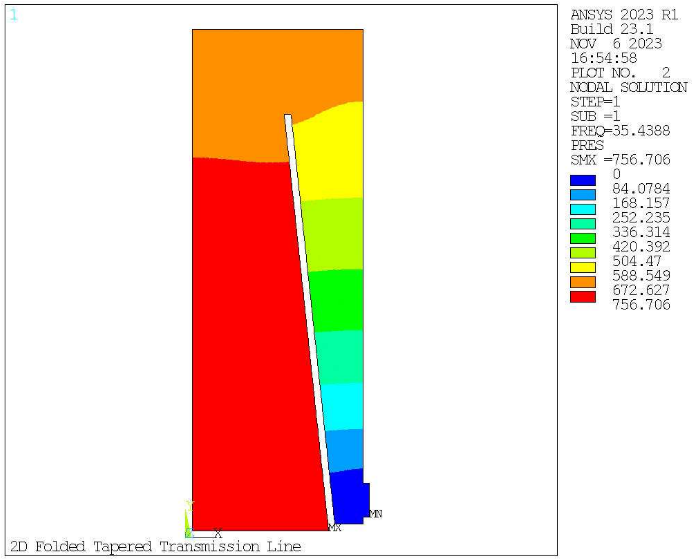
Correlation was pretty good below 300 Hz, but above 300 Hz two problems were observed. First, the measurements show more peaks and nulls than the calculated results. Second, the measurements roll off while the calculated results are flatter (align the troughs between last six peaks).

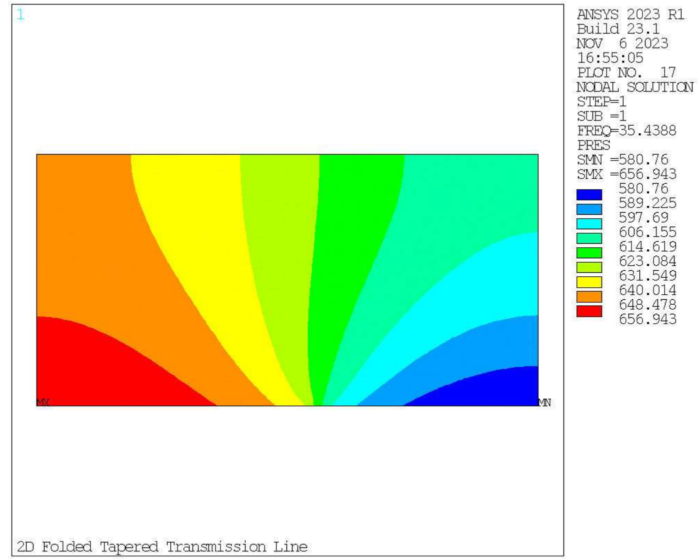
Finite Element Results and Advanced Corner Modeling





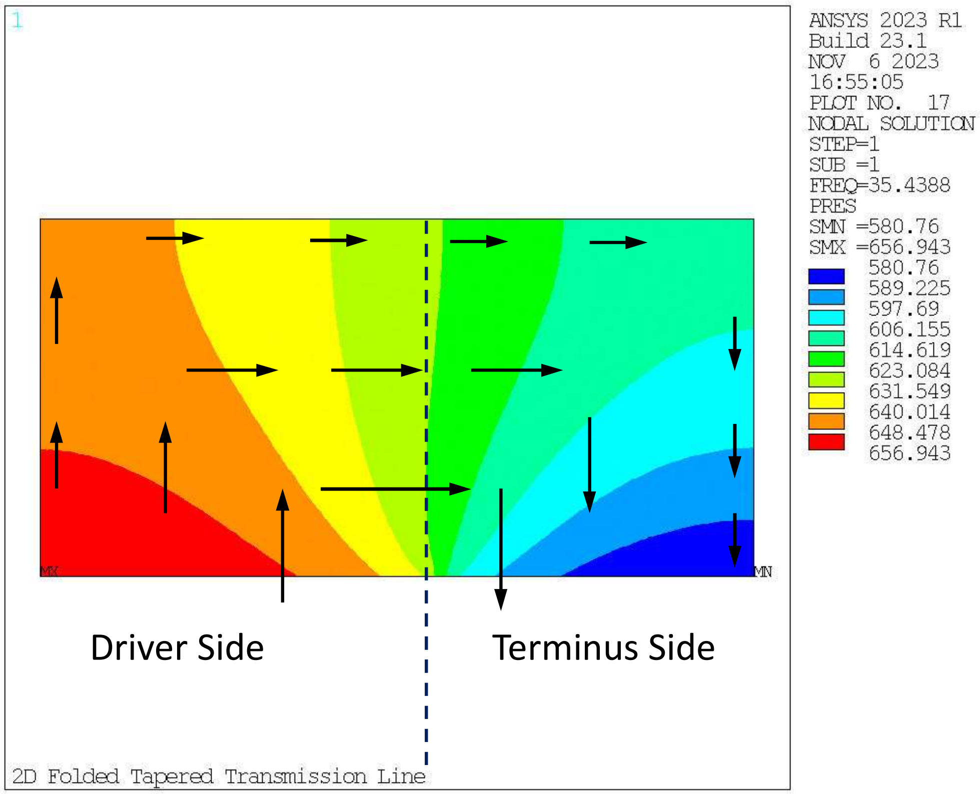
The plots above show the pressure profile in the Satori TL enclosure for the quarter wavelength standing wave at the tuning frequency of approximately 35 Hz. The left plot shows the entire enclosure while the right plot only shows the 180-degree fold at the top of the enclosure. These are normalized result. The pattern/distribution is important, but the absolute pressure magnitudes are meaningless.





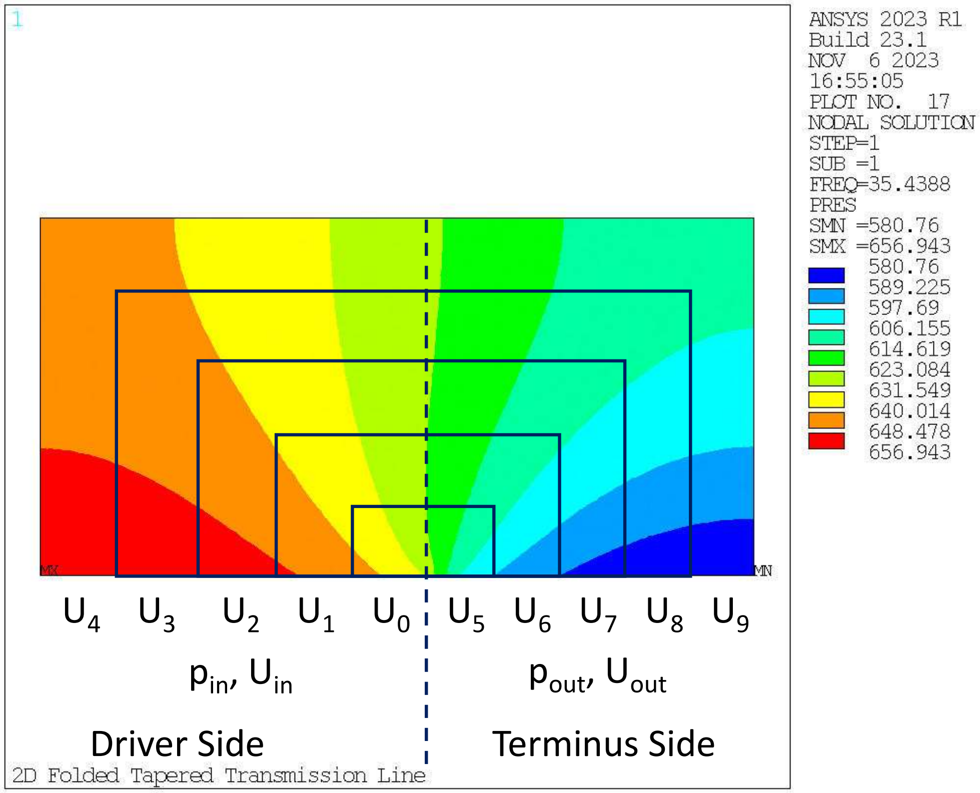
In the left plot, the pressure profile is perpendicular to the axial path, especially in the two vertical lengths. The volume velocity oscillates normal to the lines of constant pressure and is proportional to the gradient (change of pressure with length), so in the two vertical lengths it is constant across the cross-sections. These regions of the TL are consistent with the assumptions on slide 7.

The right plot shows the pressure distribution in the 180-degree fold. The pressure contours are essentially constant across the axial path which is consistent with the assumptions of slide 7. But the gradient of the pressure decreases (larger distance between pressure contours) as you move from the inside to the outside of the fold. The oscillating velocity is not constant across the cross-section which is inconsistent with the assumptions on slides 7.



Looking at the pressure gradient as it transitions through the 180-degree fold you can see a fan-like pattern. The pressure gradient along the inside of the fold is much higher than the gradient along the outside of the fold. Estimating and sketching in oscillating velocity arrows shows the non uniform velocity profile when moving outward along a cross-sectional areas.

The lines of constant pressure are also always normal to the exterior walls and dividing panel, so the oscillating velocity is parallel to these boundaries.. The pressure profile going in and coming out of the fold will return to being constant across the cross-sectional area normal to the TL's axial path.



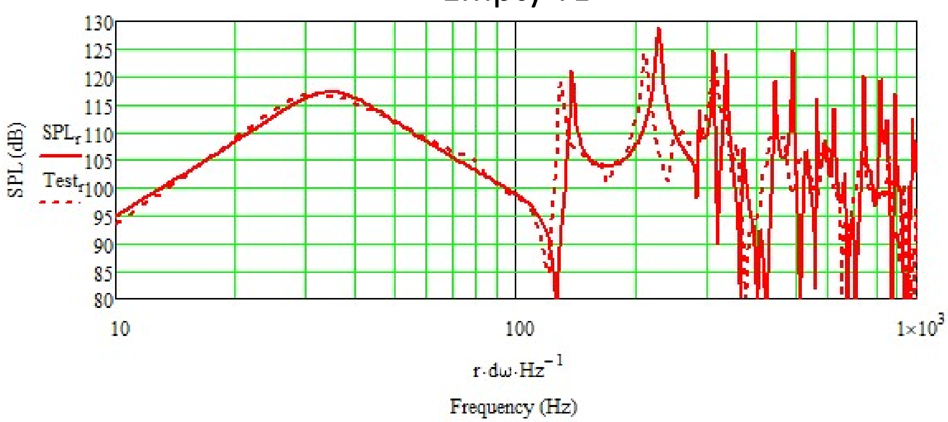
The advanced corner modeling method breaks up the fold into many parallel paths. The pressures, p_{in} and p_{out}, at each end of the different paths on each side of the fold are assumed to be uniform while the different volume velocities in the paths are the unknowns. The sum of the different path volume velocities on each side equal U_{in} and U_{out} respectively.

Solving for p_{in}, p_{out}, U_{in}, and U_{out} yields a transfer matrix that describes the acoustics of either a 90-degree or 180-degree bend or fold. Notice that the entire air volume is now used in describing the acoustics of the corner. The programming for this method has been set up to allow the number of parallel paths as a variable, at left 5 paths are shown but it could just as easily be 50 paths (but much harder to sketch).

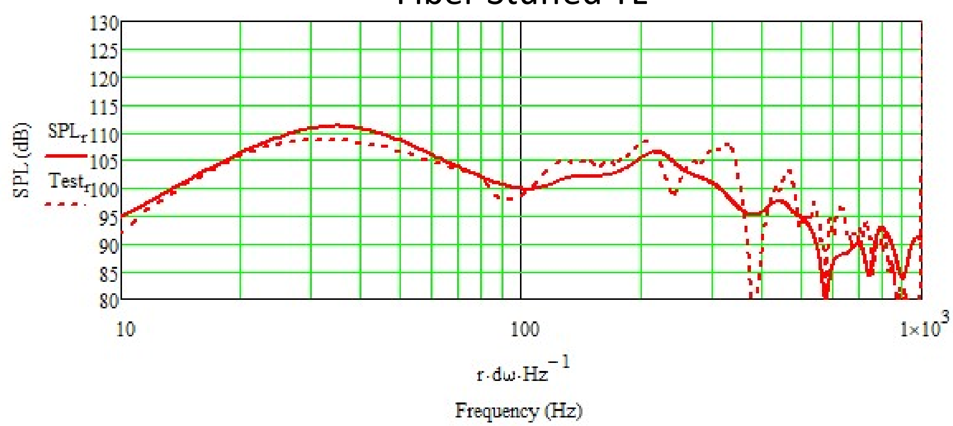
More information about modeling parallel paths is contained in the two references.

Terminus Calculated and Measured SPL Responses for the Satori Transmission Line with Advanced Corner Modeling

Empty TL

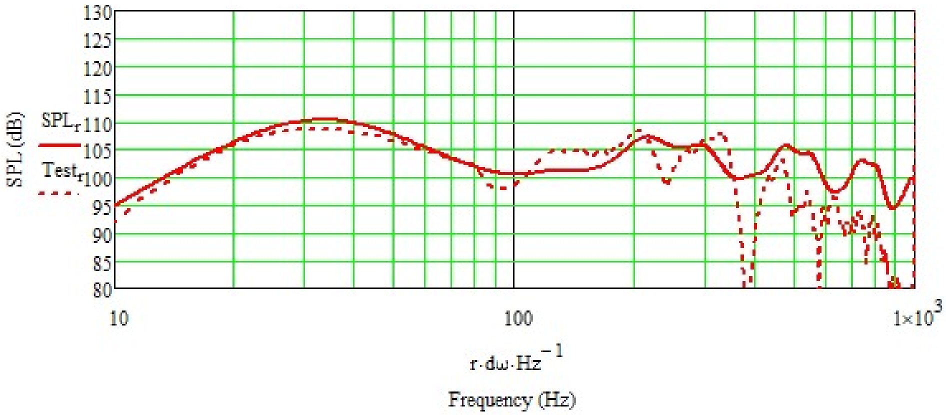


Fiber Stuffed TL

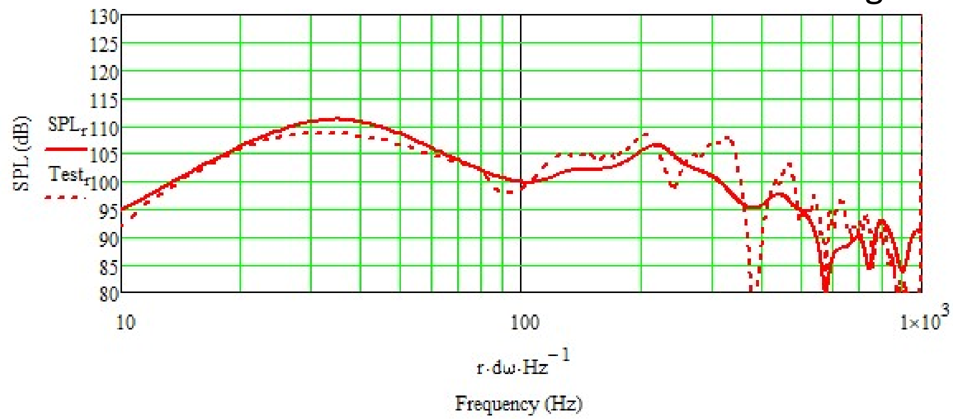


The two plots shown above contain the calculated (solid red curve) and measured (dashed red curve) terminus near field SPL responses. Correlation has improved with the advanced corner modeling (10 parallel paths used) method. There are more peaks and dips seen in the empty TL calculations and the roll off previously observed in the measurements above 300 Hz is now predicted.

Fiber Stuffed TL – Centerline Method



Fiber Stuffed TL – Advanced Corner Modeling



Some Observations :

- At low frequencies the method for modeling the corner is not critical, the results are essentially the same.
- As frequency increases, the difference in lengths of the inner and outer paths reaches half a wavelength at 275 Hz. For the advanced corner modeling the terminus SPL output starts to roll off at about 300 Hz, probably not a coincidence.
- Thinking about corner treatments such as curved inserts or 45-degree wedges, these shorten the outer path length which probably raises the frequency where the terminus output starts to roll-off. I need to simulate this construction feature; it may not be an advantage for suppressing the higher harmonics

Key Take Aways from Part 3

- I believe that the parallel path methods used in the Advance Corner Modeling is another step forward in understanding and designing quarter wavelength loudspeaker systems. The number and placement of folds and bends along the length can now be used as a design variable to mitigate the higher harmonics and reduce the amount of damping material (meaning more bass output) in the final enclosure.
- This is the first use of the method, so refinements and advances are still being developed. There is much more to explore and learn using the method.
- Additional areas of applicability to be investigate are BLHs, which typically contain many folds, curved path profiles and terminus/mouth shapes that are not consistent with a spherical wave output.
- When I first started exploring TL design methods, over 30 years ago, the focus was primarily on fiber damping of the standing waves. Slowly I have shifted my focus to the geometry of the line itself with damping material being less important in the final design.

GEOMETRY IS EVERYTHING!

References

Acoustics of Ducts and Mufflers 2nd Edition by M. L. Munjal, Wiley 2014 (Chapter 4, pages 147 – 150).

Passive Damping Mechanism of Herschel-Quincke Tubes for Pressure Pulsations in Piping Systems by Thomas Lato, University of Ontario Masters Degree Thesis.
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