Classic Transmission Line Enclosure Alignment Tables

Martin J. King
40 Dorsman Dr.
Clifton Park, NY 12065
MJKing57@aol.com

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Introduction :

Ever since I first made my original MathCad transmission line worksheets available, the subject of alignment tables has come up again and again. Reasons vary; some people had difficulty using the worksheets while others just wanted a starting geometry for input into the worksheets. When you design your first transmission line enclosure using the MathCad worksheets, it can be a little hard to get started. Learning how to use MathCad while also learning a new enclosure design methodology is not easy for everybody.

People are comfortable with the commonly available alignment tables for closed and ported enclosures. Box size and tuning frequency are expressed as functions of a driver's Thiele / Small parameters. Alignment tables represent a cookbook process with predictable results for designing closed or ported enclosures. Similar general alignment tables for transmission line enclosures would allow quick scoping analyses of enclosure geometries for different drivers under consideration. The scoping calculations could become the basis of a final design or the starting point for further optimization using the MathCad worksheets.

As I continued to work on transmission line enclosure designs, I collected a number of interesting observations in my personal notes. Keeping in mind the requests for alignment tables, about a year ago I thought I saw a method for specifying the enclosure geometry as a function of a driver's Thiele / Small parameters. Please recognize, this is only one method and there are probably many other approaches for defining alternate transmission line alignment tables that I have not considered.

Recently, I started seriously exploring this path for deriving a set of transmission line alignment tables. The resulting method was described in my first alignment table document several months ago. After making this first set of alignment tables available on my website, many people tried them and provided constructive feedback on how to make the tables better and more accurate. Based on these responses, a second set of alignment tables has been prepared which incorporates most of these comments. I believe that this second set of alignment tables does a better job of sizing classic transmission line enclosures for a wider range of drivers.

Method Derivation :

The alignment tables are derived for classic transmission line geometries. I define a classic transmission line as a pipe or labyrinth (expanding, straight, or tapered) where the length has been set so that the frequency of the first quarter wavelength standing wave closely coincides with the driver's resonant frequency. Fiber stuffing is used in the pipe to attenuate the higher harmonics of the fundamental quarter wavelength resonance. Examples of this type of geometry are shown in Figure 1. Everything that follows is addressing these geometries. I do not consider any of my mass loaded designs to be classic transmission lines so they fall outside of these alignment tables.

Figures 2 and 3 show simplified acoustic and electrical equivalent circuit models for a classic transmission line with the driver mounted at the closed end. The circuits can

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be transformed into ported and closed box equivalent circuit models by changing the impedances, Z_{al} and Z_{el}, associated with the transmission line enclosure. Due to the multiple resonances associated with any pipe geometry, the acoustic and electrical impedances have both magnitude and phase, are functions of frequency, and contain a series of peaks and nulls. For example, the acoustic and electrical impedances of a lightly stuffed classic transmission line are shown in Figures 4 and 5 respectively. The impact of these impedances on the simple circuit models can be surmised from the plots in Figures 4 and 5.

At the first pipe resonance, 30 Hz in Figure 4, the acoustic impedance Z_{al} reaches a maximum. This large acoustic impedance in series with the driver's acoustic circuit elements, see Figure 2, will cause U_d to become very small. The driver's motion will be significantly attenuated just like in a ported box design at the system tuning frequency. The pressure acting on the back of the driver cone will reach a maximum. The air velocity at the open end will also be a maximum. Almost all of the system's acoustic output will be from the open end of the lightly stuffed transmission line.

Looking at Figure 5, the transmission line electrical impedance Z_{el} has a minimum at the first pipe resonance. This minimum electrical impedance will tend to short the driver's electrical circuit elements which are in parallel as shown in Figure 3. Graphically, this can be seen in the plot in Figure 6 which shows the driver's infinite baffle electrical impedance (blue curve) and the transmission line's electrical impedance (brown curve). The plot shown in Figure 7 displays the driver's infinite baffle impedance (blue curve) and the combined transmission line system's impedance (red curve). Notice the double humped impedance curve for the lightly stuffed transmission line speaker system shown by the red curve in Figure 7. It was the parallel impedances in Figure 6 forming the double humped impedance curve in Figure 7 that was the key to setting up these alignment tables.

When the transmission line speaker's system impedance curve is split into the driver impedance and the transmission line impedance, as shown in Figure 6, it becomes obvious that the adjustable variables relate to the first minimum in the transmission line's impedance curve. The driver's Thiele / Small properties are defined so the transmission line geometry is all that can be adjusted. The frequency and depth of this first minimum determines the required geometry for a classic transmission line enclosure.

The acoustic impedance for an open ended transmission line, as derived on page 6 of the "Method Derivation" section in the Transmission Line Theory articles, is shown below.

$$Z_{acoustic}(\omega) = \frac{I\,\rho\,c^2\,(\alpha^2+\beta^2)\,(\mathbf{e}^{(I\,L\,\beta)} - \mathbf{e}^{(-I\,L\,\beta)})}{\omega\,S_0\,((\alpha+I\,\beta)\,\mathbf{e}^{(I\,L\,\beta)} - (\alpha-I\,\beta)\,\mathbf{e}^{(-I\,L\,\beta)})}$$

By moving the plane wave specific acoustic impedance (ρc) and the transmission line cross-sectional area (S_0) over to the left side of the equation, a dimensionless expression for the shape of the acoustic impedance remains. The dimensionless expression for the acoustic impedance shape is a function of frequency, length, and area ratio S_L/S_0.

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$$\frac{Z_{acoustic}(\omega)\, S_0}{\rho\, c} = \frac{I\, c\, (\alpha^2 + \beta^2)\, (\mathbf{e}^{(I\, L\, \beta)} - \mathbf{e}^{(-I\, L\, \beta)})}{\omega\, ((\alpha + I\, \beta)\, \mathbf{e}^{(I\, L\, \beta)} - (\alpha - I\, \beta)\, \mathbf{e}^{(-I\, L\, \beta)})}$$

The right side of the equation above is independent of the absolute cross-sectional area of the transmission line enclosure. By substituting a frequency and an area ratio S_L/S_0 into the right hand side of the expression, an effective length and a peak value of the shape function can be determined. Tables 1 and 2 contain the effective lengths and the peak shape function magnitudes for classic transmission lines tuned between 20 Hz and 70 Hz and having area ratios S_L/S_0 between 0.1 and 10.

Simplifying the previous equation by substituting a peak shape function value (D_Z), from Table 2, for the right hand side yields the following result.

$$\frac{Z_{acoustic}\, S_0}{\rho\, c} = D_Z$$

By definition, acoustic impedance is related to electrical impedance by the following general expression.

$$Z_{electrical} = \frac{B^2\, l^2}{Z_{acoustic}\, S_d{}^2}$$

Inserting the derived relationship for the acoustic impedance into this definition of the electrical impedance leaves the following.

$$Z_{electrical} = \frac{S_0\, B^2\, l^2}{\rho\, c\, D_Z\, S_d{}^2}$$

In Figure 6, the minimum value of the transmission line's equivalent electrical impedance will be set to a scaling factor times the voice coil's DC resistance. This scaling factor is the resistance function (D_R).

$$D_R\, R_e = \frac{S_0\, B^2\, l^2}{\rho\, c\, D_Z\, S_d{}^2}$$

Finally solving for the cross-sectional area at the closed end of the transmission line S_0 produces the required equation.

$$\boxed{S_0 = \frac{\rho\, c\, S_d{}^2\, D_Z\, D_R\, R_e}{B^2\, l^2}}$$

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If a value for D_R is defined, the cross-sectional area at the closed end of the transmission line can be calculated. Table 3 contains recommended values for the resistance function for different values of driver Q_{ts}. Returning to the plot in Figure 6, the depth of the first null in the electrical impedance is being specified by calculating the value $D_R\ R_e$. For values of Q_{ts} outside of this range, extrapolation can be used to determine the appropriate value of the electrical impedance. The values of Q_{ts} contained in Table 3 span most suitable drivers for transmission line enclosures.

Having calculated S_0, and knowing S_L/S_0 and the effective length, the geometry of the classic transmission line enclosure is completely defined. With this known geometry the only open issue is the driver location along the length of the transmission line. If the driver is mounted at the closed end of the transmission line, then all of the higher harmonics of the fundamental quarter wavelength resonance will be excited. By offsetting the driver the excitation of certain higher modes can be reduced and even suppressed.

Table 4 contains the maximum recommended driver offset positions. At these driver positions, it is possible to almost completely suppress the second mode (three-quarter wavelength) and every other quarter wavelength mode (seven-quarter wavelength, eleven-quarter wavelength …) above this point. One consequence of offsetting the driver is a reduction in the excitation applied to the fundamental quarter wavelength mode, the tuning frequency of the line, and some reduction in bass extension. By placing the driver someplace between the closed end (ξ = 0) and the maximum offset ratio shown in Table 4, a compromise response results. A commonly found recommendation for the driver offset ratio ξ is 0.2.

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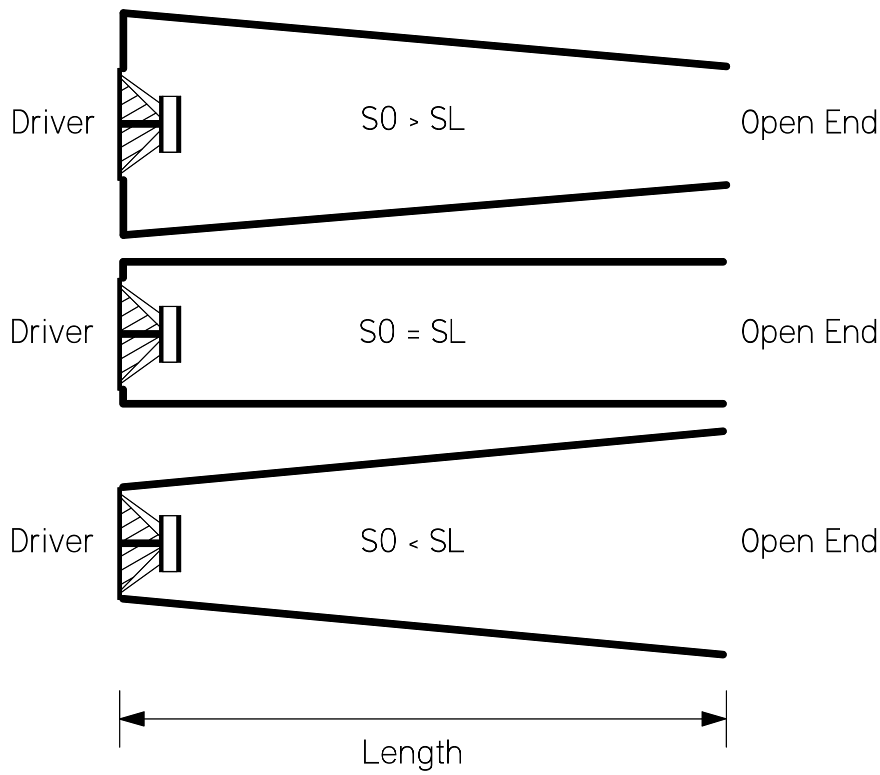
Figure 1 : Classic Transmission Line Geometries



where : S_0 = cross-sectional area at the closed end
S_L = cross-sectional area at the open end
L = length of the pipe
D = density of fiber stuffing

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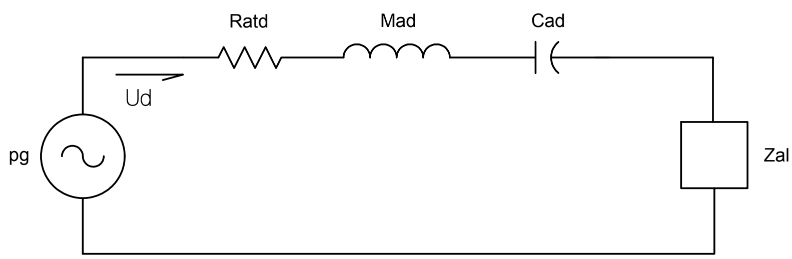
Figure 2 : Acoustic Equivalent Circuit for a Simple Transmission Line Speaker



where :

p_g = pressure source
$= (e_g\ Bl) / (S_d\ R_e)$

R_{ad} = driver acoustic resistance
$= (Bl^2 / S_d^2)\ [Q_{ed} / ((R_g + R_e)\ Q_{md})]$

R_{atd} = total acoustic resistance
$= R_{ad} + (Bl)^2 / [S_d^2\ ((R_g + R_e) + j\omega\ L_{vc})]$

C_{ad} = driver acoustic compliance
$= V_{ad} / (\rho_{air}\ c^2)$

M_{ad} = driver acoustic mass
$= (f_d^2\ C_{ad})^{-1}$

Z_{al} = transmission line acoustic impedance

U_d = driver volume velocity
$= S_d\ u_d$

u_d = driver cone velocity

then :

u_L = terminus air velocity
$= \varepsilon\ u_d$

ε $= u_L / u_d$

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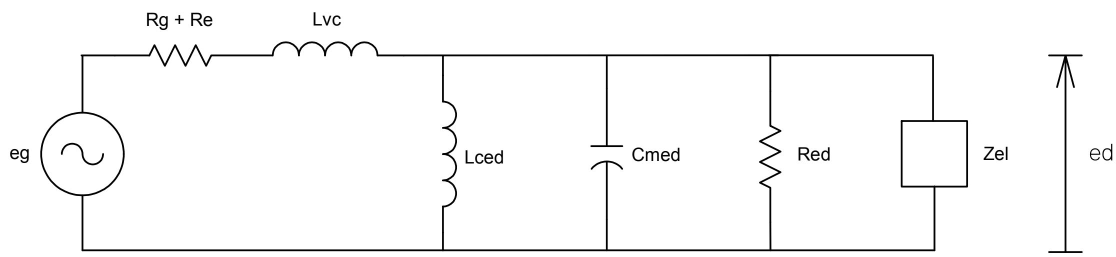
Figure 3 : Electrical Equivalent Circuit for a Simple Transmission Line Speaker



where :

e_g = voltage source
= 2.8284 volt

R_g+R_e = electrical resistance of the amplifier, cables, and voice coil

L_{vc} = voice coil inductance

L_{ced} = inductance due to the driver suspension compliance
= $[C_{ad} (Bl)^2] / S_d^2$

C_{med} = capacitance due to the driver mass
= $(M_{ad} S_d^2) / (Bl)^2$

R_{ed} = resistance due to the driver suspension damping
= $R_e (Q_{md} / Q_{ed})$

Z_{el} = transmission line equivalent electrical impedance
= $(Bl)^2 / (S_d^2 Z_{al})$

e_d = $Bl\ u_d$

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Figure 4 : Transmission Line Acoustic Impedance

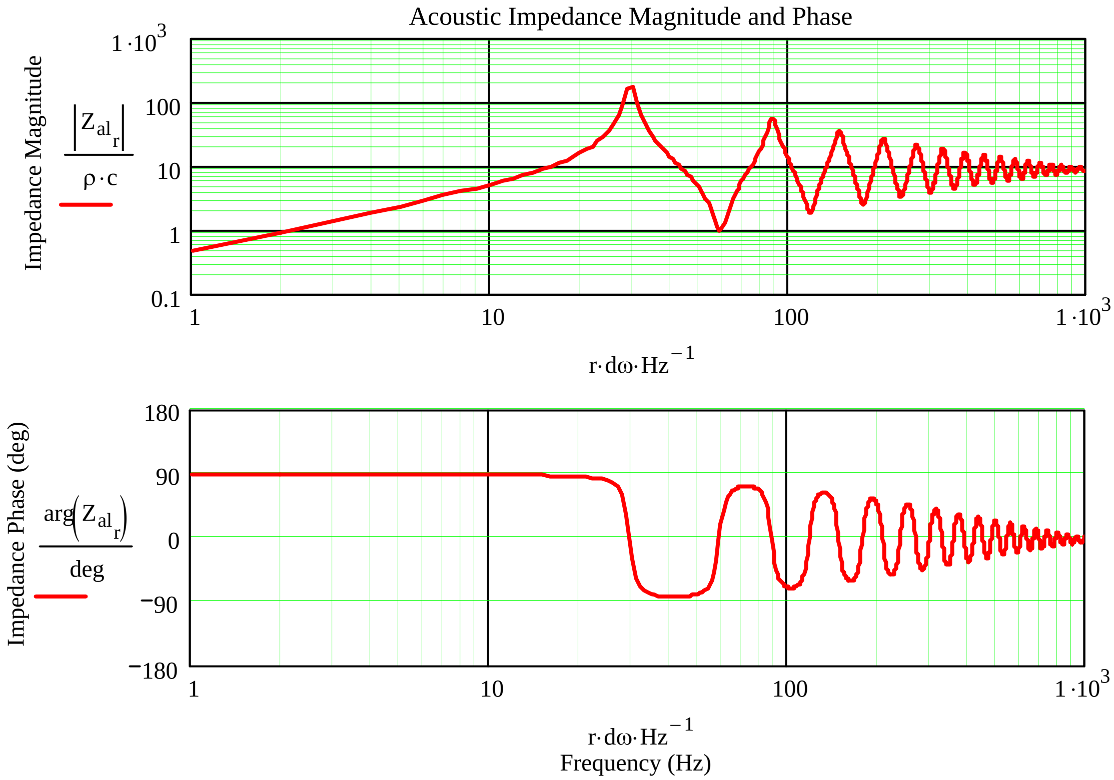

Figure 5 : Transmission Line Electical Impedance

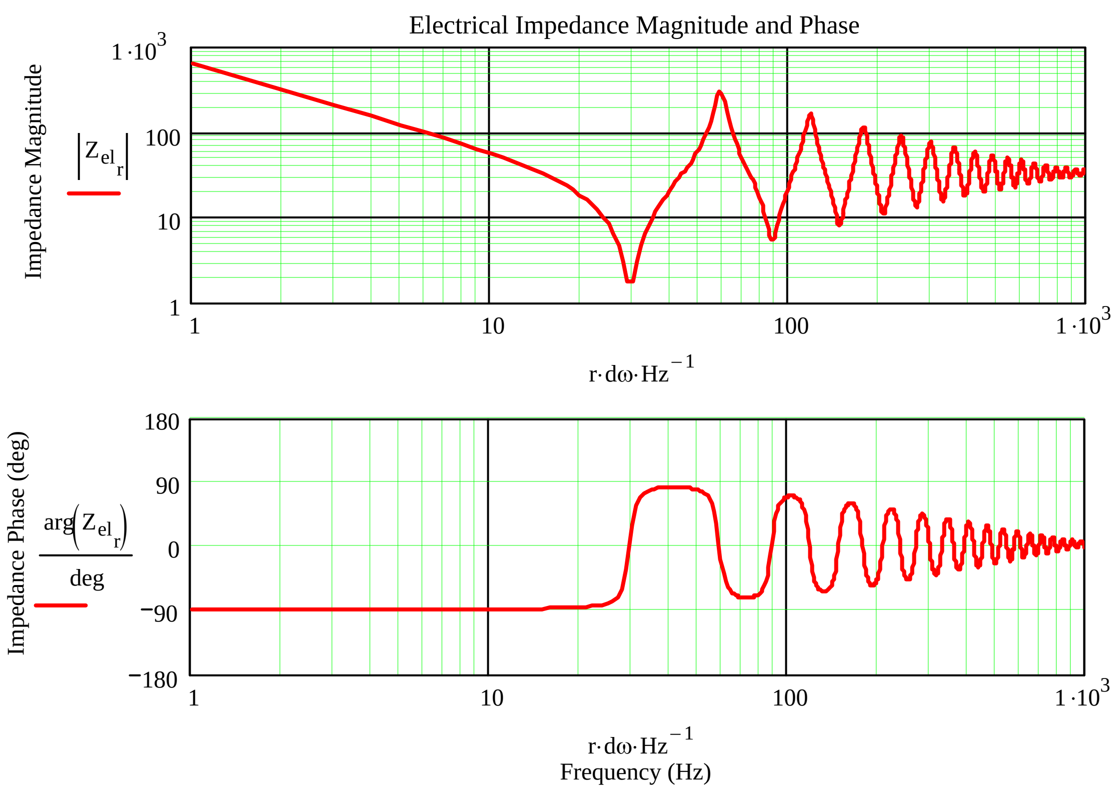

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Figure 6 : Electrical Impedance Magnitudes

Blue Curve – Driver in an Infinite Baffle Impedance
Brown Curve – Transmission Line Electrical Impedance

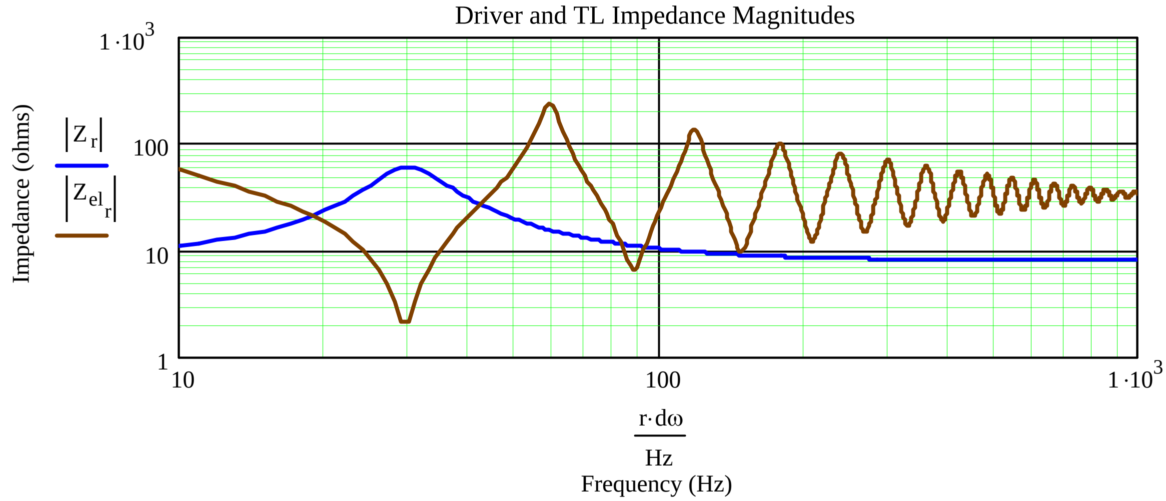

Figure 7 : Transmission Line System Impedance

Blue Curve – Driver in an Infinite Baffle Impedance
Red Curve – Transmission Line System Impedance

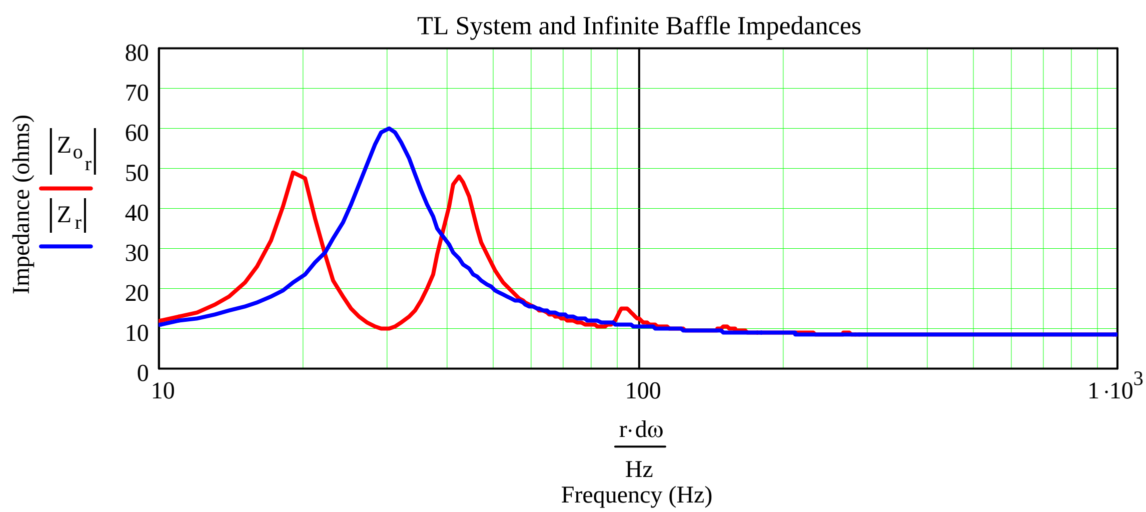

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Table 1 : Transmission Line Effective Length as a Function of Frequency and Area Ratio

	Transmission Line Effective Length (inches)										
	Frequency (Hz)										
SL/S0	20	25	30	35	40	45	50	55	60	65	70
10	238.8	191.0	159.2	136.5	119.4	106.1	95.5	86.8	79.6	73.5	68.2
5	221.4	177.1	147.6	126.5	110.7	98.4	88.6	80.5	73.8	68.1	63.3
3	205.7	164.6	137.1	117.5	102.9	91.4	82.3	74.8	68.6	63.3	58.8
2	192.1	153.7	128.1	109.8	96.1	85.4	76.8	69.9	64.0	59.1	54.9
1	168.0	134.4	112.0	96.0	84.0	74.7	67.2	61.1	56.0	51.7	48.0
0.5	145.5	116.4	97.0	83.1	72.8	64.7	58.2	52.9	48.5	44.8	41.6
0.333	133.5	106.8	89.0	76.3	66.8	59.3	53.4	48.5	44.5	41.1	38.1
0.2	119.9	95.9	79.9	68.5	60.0	53.3	48.0	43.6	40.0	36.9	34.3
0.1	103.4	82.7	68.9	59.1	51.7	46.0	41.4	37.6	34.5	31.8	29.5

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Table 2 : Peak Value of Shape Function D_Z as a Function of Frequency and Area Ratio

Peak Value of Shape Function - D_Z

	Frequency (Hz)										
SL/S0	20	25	30	35	40	45	50	55	60	65	70
10	4.392	5.490	6.588	7.686	8.784	9.882	10.980	12.078	13.176	14.274	15.372
5	7.766	9.708	11.649	13.591	15.532	17.474	19.415	21.357	23.298	25.240	27.181
3	11.059	13.824	16.589	19.353	22.118	24.883	27.648	30.412	33.177	35.942	38.707
2	14.025	17.531	21.038	24.544	28.050	31.556	35.063	38.569	42.075	45.581	49.088
1	19.429	24.286	29.144	34.001	38.858	43.715	48.573	53.430	58.287	63.144	68.002
0.5	24.794	30.993	37.191	43.390	49.588	55.787	61.985	68.184	74.382	80.581	86.779
0.333	27.820	34.775	41.730	48.685	55.640	62.595	69.550	76.505	83.460	90.415	97.370
0.2	31.494	39.368	47.241	55.115	62.988	70.862	78.735	86.609	94.482	102.356	110.229
0.1	36.482	45.603	54.723	63.844	72.964	82.085	91.205	100.326	109.446	118.567	127.687

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Table 3 : Resistance Factor D_R

Qtd	D_R
0.20	0.1858
0.30	0.1313
0.40	0.0950
0.50	0.0788
0.60	0.0688
0.70	0.0625

Table 4 : Driver Offset Ratio

SL/S0	ξ
10	0.416
5	0.393
3	0.377
2	0.365
1	0.349
0.5	0.339
0.333	0.336
0.2	0.336
0.1	0.336

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Sample Design Problem :

As an example of the alignment table method, my Focal two-way transmission line geometry will be re-derived using the alignment tables and then compared to what was actually built. For this design, MathCad calculations and final system measurements are available. Details of this speaker design can be found under Project #1 on my website (www.quarter-wave.com).

1) Starting with the measured Focal 8V 4412 Thiele / Small parameters.

Property	Average	Units
f_d	33.7	Hz
V_{ad}	66.9	liters
Q_{td}	0.38	
Q_{ed}	0.44	
Q_{md}	2.57	
R_e	7.7	ohm
S_d	0.022	m^2
C_{ad} (10^{-7})	4.83	m^5/N
M_{ad}	46.5	kg/m^4
R_{ad}	3829	N sec/m^5
C_{md} (10^{-3})	0.98	m/N
M_{md}	22.8	gm
R_{md}	1.882	gm/sec
C_{med}	270.2	μF
L_{ced}	82.9	mH
R_{ed}	45.0	ohm
Bl	9.2	N/amp

2) Assume $S_L/S_0 = 1$. From Tables 1, 2, and 3 the following values are determined using 35 Hz as the system's tuning frequency. The actual design tuned the transmission line to 47 Hz resulting in a shorter length.

$L_{effective}$ = 96 in = 2.438 m

$D_Z = 34.001$

$D_R = 0.102$

3) Calculate S_0/S_d. Using S_d from the table above, the numerical value for S_0 can be calculated. The very last equation at the bottom of page 3, the equation in the red box, is used to perform this calculation. Be careful with the units of various terms.

$S_0/S_d = \rho\ c\ S_d\ D_Z\ D_R\ R_e\ /\ (Bl)^2$

$S_0/S_d = (1.21\ kg/m^3)(342\ m/sec)(0.022\ m^2)(34.00)(0.102)(7.7\ ohms)\ /\ (9.2\ N/amp)^2$

$S_0/S_d = 2.872$

$S_0 = 2.872\ S_d = 2.872\ (0.022\ m^2) = 0.063\ m^2 \sim 98\ in^2$ $(S_L/S_0 = 1$ so $S_L = S_0)$

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4) Calculate the actual length by removing the open end boundary condition correction from the effective length. This is the correct line length to use in the MathCad transmission line worksheets. The acoustic impedance at the open end adds 0.085 m, or ~ 3.3 inches, to the actual physical length for this cross-sectional area.

$$L_{actual} = L_{effective} - 0.6\, (S_L/\pi)^{1/2}$$

$$L_{actual} = 2.438\text{ m} - 0.6\,[\,(0.063\text{ m}^2)\,/\,\pi\,]^{1/2} = 2.438\text{ m} - 0.085\text{ m} = 2.353\text{ m}$$

5) Comparing the alignment table results with the actual design shows some differences in the transmission line geometries.

TL Property	Alignment Table	Actual Design	Units
Length	2.353	1.819	(m)
S_0/S_d	2.872	3.000	---

The properties of the actual design and the alignment table design, as shown in the table above, were entered into the “TL Offset Driver” MathCad worksheet and the results are plotted in Figures 8 and 9. The driver was offset six inches from the closed end and the stuffing density was 0.5 lb/ft^3 for the entire length of the line.

The alignment tables were derived assuming the transmission line is tuned to the driver’s resonant frequency. Comparing Figures 8 and 9, the differences in the responses result from the tuning frequency of the actual design being greater than the driver resonant frequency. If the stuffing were only placed in the first 3/4’s of the length, the alignment table transmission line performance would closely match the actual design’s performance. This simulation result is shown in Figure 10.

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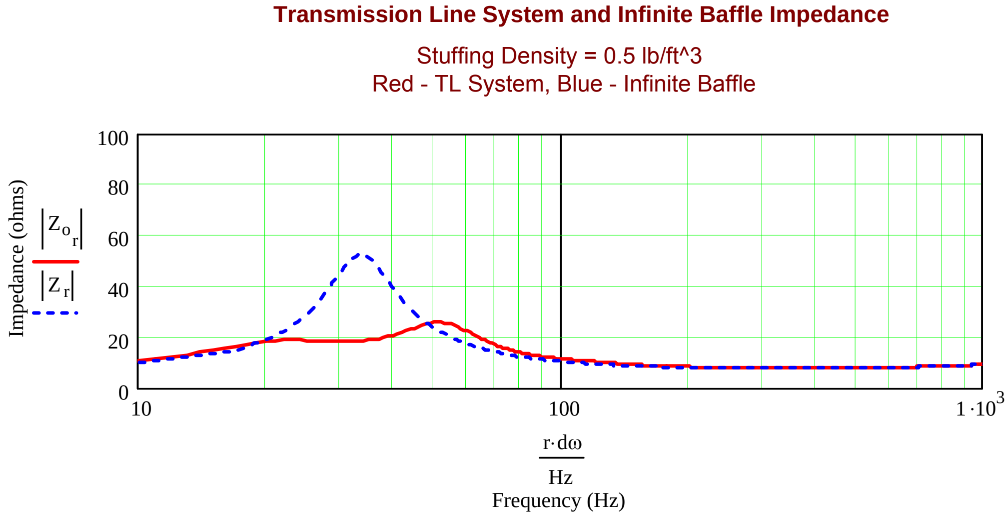
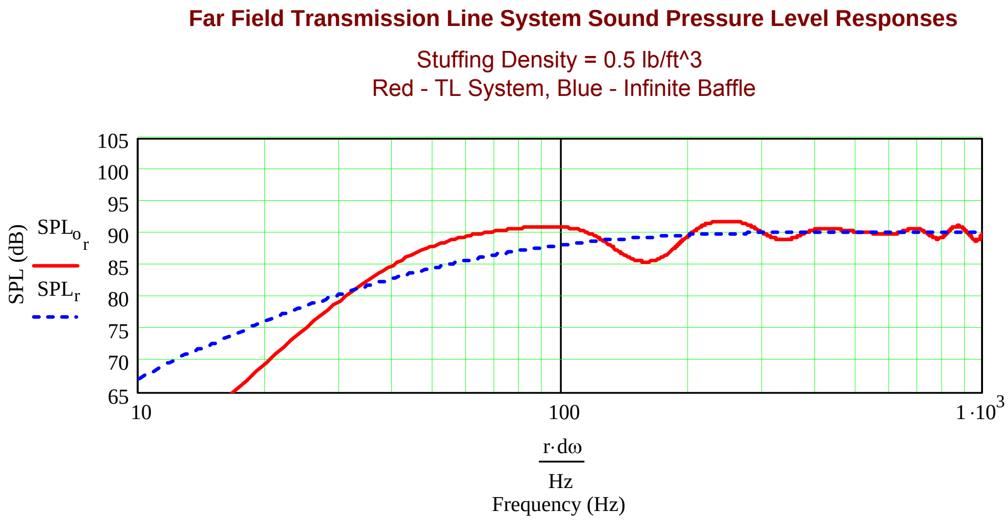
Figure 8 : Focal 8V 4412 Driver in a Transmission Line – As Built Design





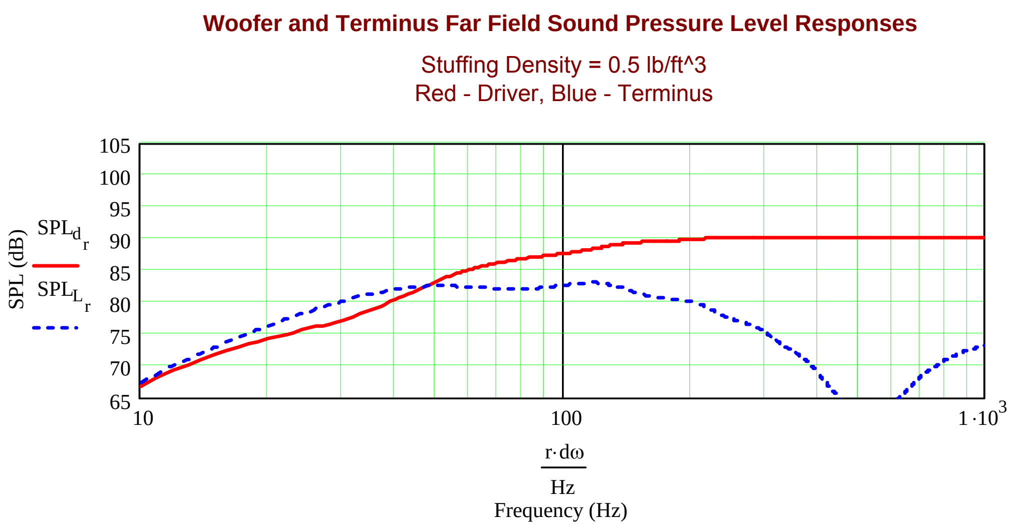


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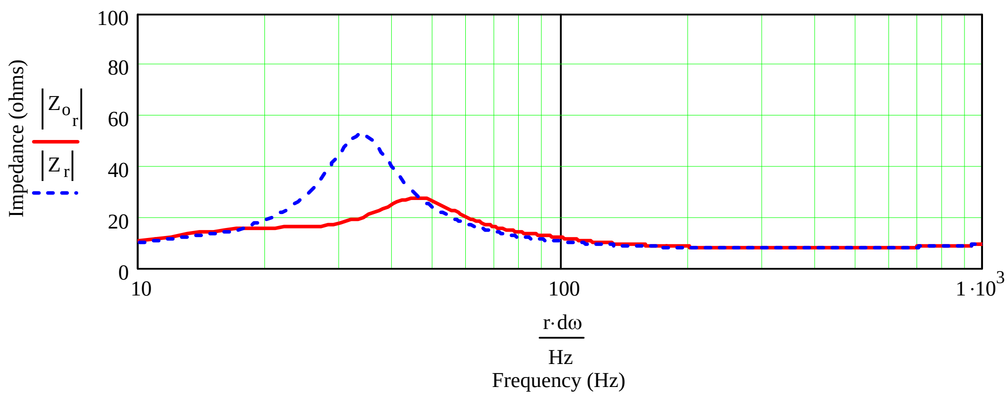
Figure 9 : Focal 8V 4412 Driver in a Transmission Line – Alignment Table Design

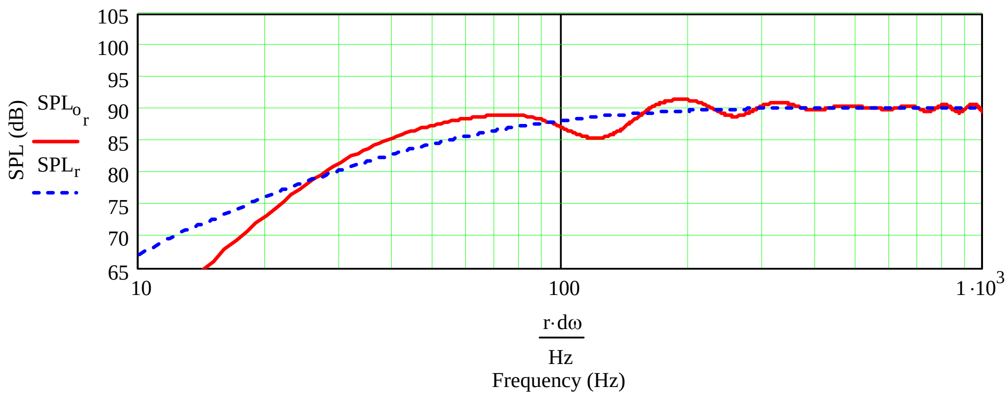
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - Driver, Blue - Terminus

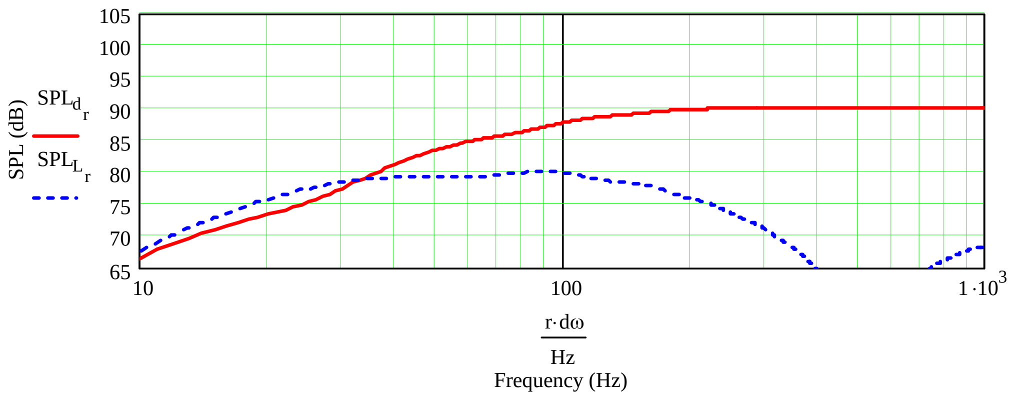


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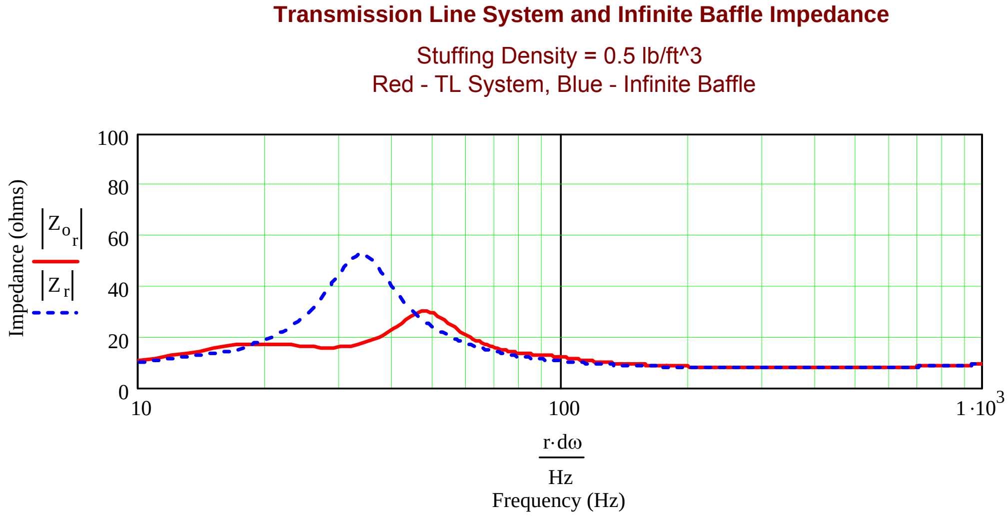
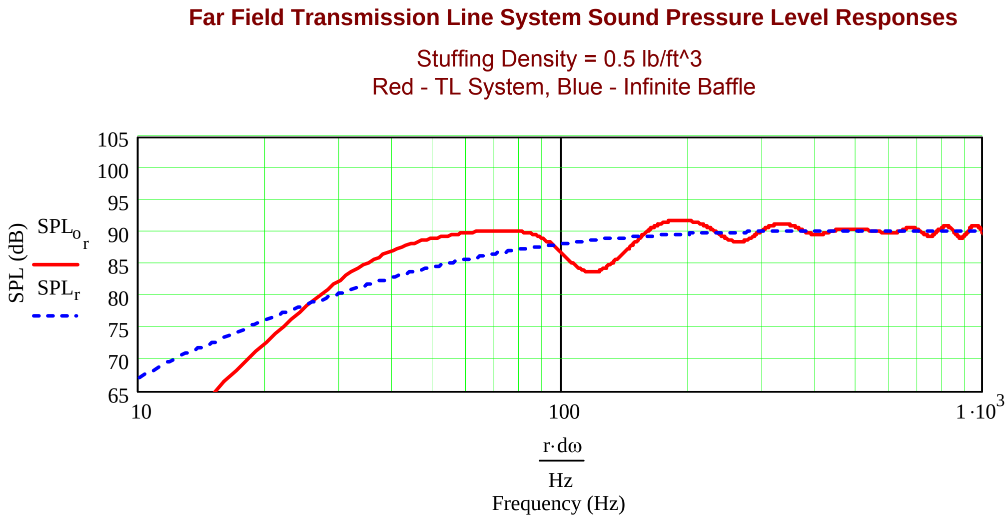
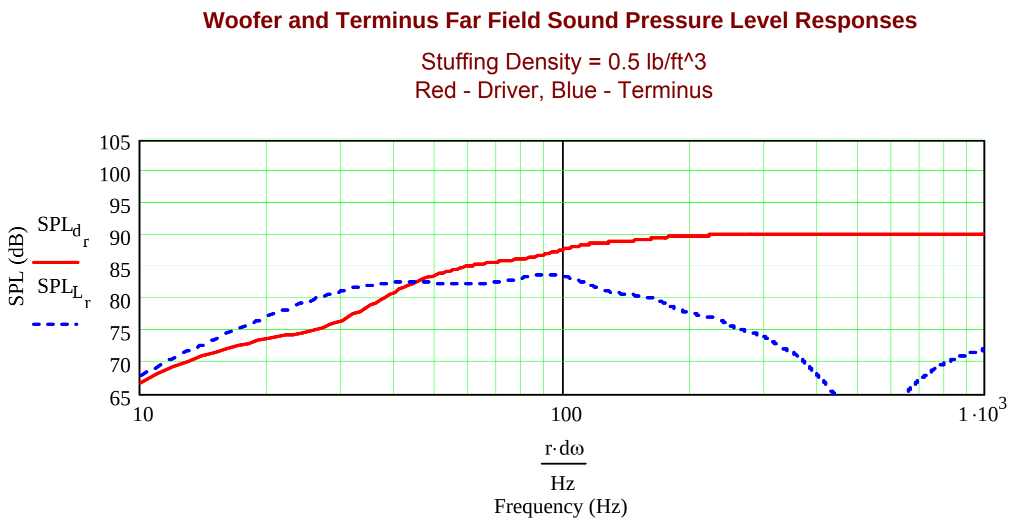
Figure 10 : Focal 8V 4412 Driver in a Transmission Line – Alignment Table Design w/ Optimized Stuffing Placement







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Conclusions :

A set of alignment tables for classic transmission line enclosures has been derived that span the following range of Thiele / Small driver parameters and cross-sectional area ratios.

$$20\ \text{Hz} < f_d < 70\ \text{Hz}$$
$$0.2 < Q_{td} < 0.7$$
$$0.1 < S_L/S_0 < 10$$

The results from these tables determine a simple classic transmission line geometry that does not include any sudden changes in the cross-sectional area. Mass loading of the transmission line's open end is not included in these tables. The transmission line geometry must be a smooth linear transition, along the length, from the closed end area S_0 to the open end area S_L as shown in Figure 1.

From these alignment tables, a basic geometry definition is determined which can be used to build a transmission line speaker system or as a starting point for further MathCad optimization. After using these alignment tables, I still strongly recommend double checking the results by putting the driver's Thiele / Small parameters and the calculated geometry into the "TL Offset Driver" MathCad worksheet. Further optimization may still be possible.

I have checked the alignment tables assuming many different generic drivers. I derive the Thiele / Small parameters based on a minimum number of assumptions. I have assigned different values for R_e, Q_{td}, Q_{ed}, f_d, S_d, and SPL (at 1 m/1 W) that cover the ranges shown in the tables. My only concern with people using the alignment tables is that the units of terms in the equations will be inserted in an inconsistent manner and an erroneous result will be produced. Watch, and double check, the units being used in the equations and make sure that the calculated results have the expected units! I have attached four additional case studies to further illustrate the method and provide some insight into the resulting system responses.

Classic transmission lines exhibit ripples in the pass-band. This is a property of the design that can be mitigated by the driver placement and the location and density of the fiber stuffing. Adjusting the amount and location of fiber stuffing helps reduce the ripples but at the expense of bass performance. One scheme is to place stuffing only at the locations of the highest air velocities for the quarter wavelength modes targeted for suppression. This usually means stuffing the first 2/3's to 3/4's of the transmission line length and leaving the last 1/3 to 1/4 of the length nearly empty. In general, add or remove fiber stuffing to tune the final enclosure to your system, your room, and your personal taste.

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Acknowledgements :

In the introduction section, I mentioned that constructive feedback was received from many people after they tried the original alignment tables. I appreciate all of the feedback concerning the information, theory, designs, and MathCad software presented on my website. I take every comment seriously and try my best to respond to each person.

One individual in particular spent a significant amount of time reviewing my original alignment table method and then sent three detailed letters documenting his findings. Mr. George Augspurger provided constructive comments, methods for checking alignment tables, and sample computer simulations comparing his computer program against my MathCad worksheets. In addition, he patiently provided further explanations to help answer questions I asked regarding his comments. This correspondence has been extremely valuable and is one of the prime reasons I have revised and improved my transmission line alignment tables.

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Attachment A : Transmission Line Response as a Function of Driver Thiele / Small Parameters

The first study conducted using the alignment tables was a characterization of an empty transmission line's response as a function of the driver's Thiele / Small parameters. To perform the calculations, a generic driver was formulated by defining f_d, R_e, Q_{md}, V_{ad}, and S_d. After selecting a value for Q_{td}, the remaining parameters Bl and SPL (for 1 watt input at 1 m distance) were calculated. Then by entering the alignment tables, the geometry was determined and a MathCad simulation was performed using the "TL Open End" worksheet. Table A1 contains the properties of the generic drivers included in the study. Table A2 contains the transmission line geometries derived using the alignment tables for each of these generic drivers.

Table A-1 : Generic Driver Thiele / Small Parameters

T/S Parameter	Driver Properties 0.2	0.3	0.4	0.5	0.6	0.7	Units
fd	30	30	30	30	30	30	Hz
Re	8	8	8	8	8	8	ohm
Qed	0.207	0.316	0.429	0.545	0.667	0.792	--
Qmd	6	6	6	6	6	6	--
Qtd	0.2	0.3	0.4	0.5	0.6	0.7	--
Sd	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	m^2
Vad	83.7	83.7	83.7	83.7	83.7	83.7	liter
BL	12.075	9.774	8.39	7.437	6.726	6.17	N/Amp
SPL	92.3	90.5	89.2	88.1	87.2	86.5	dB 1m/1w

Table A-2 : Transmission Line Geometry

Line Geometry	Driver Properties 0.2	0.3	0.4	0.5	0.6	0.7	Units
Leff	2.845	2.845	2.845	2.845	2.845	2.845	m
L	2.768	2.767	2.766	2.763	2.761	2.757	m
SL/S0	1	1	1	1	1	1	--
S0/Sd	2.520	2.588	2.669	2.816	3.005	3.247	--

Figures A-1 through A-6 show the calculated response for each column in Tables A-1 and A-2. From these tables and figures, a number of interesting observations can be made.

1. Comparing the impedance plots (top graph) for each driver, you will notice that for the lower Q_{ts} (higher Bl and SPL) drivers the impedance is strongly coupled to the cone's motion and that resonances of the driver and transmission line produce tall narrow peaks in the impedance curve. As Q_{ts} increases, the strength of the coupling drops and the magnitude of these peaks decreases.
2. For the low Q_{ts} drivers, a saddle exists in the system response (middle graph, red curve) between the 30 Hz tuning frequency and the next system resonance at approximately 90 Hz. As Q_{ts} increases the depth of the saddle decreases eventually becoming a broad hump. The cause of this can be seen by examining the Infinite Baffle response (middle graph, blue curve). The lower Q_{ts} drivers start rolling-off at a higher frequency compared to the high Q_{ts} drivers. As the driver response above resonance increases (rising Q_{ts}) so

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does the terminus response (bottom graph, red and blue curves). These two responses combine to fill the saddle and eventually form a small hump (middle graph, red curve). One method for smoothing these two types of responses is to tune the transmission line for a low Q_{ts} driver 5 to 10 Hz above the driver's resonant frequency and tune the transmission line for a high Q_{ts} driver 5 to 10 Hz below the driver's resonant frequency. This would be done by selecting an effective length and shape function D_Z for the redefined tuning frequency. The resistance factor D_R would not change.

3. As the Q_{ts} of the driver increases so does the size of the enclosure. This was somewhat of a surprise to me and provides some interesting options for smaller transmission line systems using low Q_{ts} drivers.
4. For tapered and expanding transmission line geometries, the response trends are similar in shape to the results presented in Figures A-1 through A-6. However, the spacing of the transmission line resonances change. This will be shown in Attachment C.

The curves shown in Figures A-1 through A-6 provide a significant amount of insight into the performance and behavior of transmission lines for drivers with different Thiele / Small parameters. These curves are intended to provide some feeling for the expected response of a driver in a transmission line that has been sized using the alignment tables.

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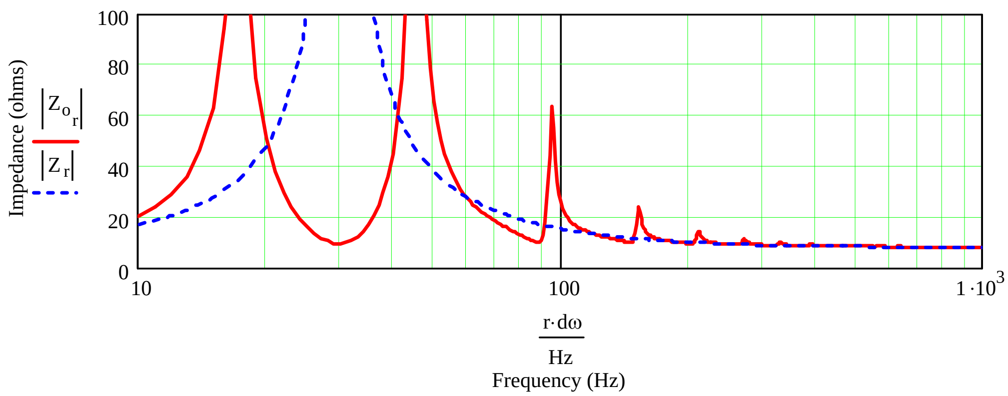
Figure A-1 : Generic Driver in a Straight Unstuffed Transmission Line
Q_{ts} = 0.2

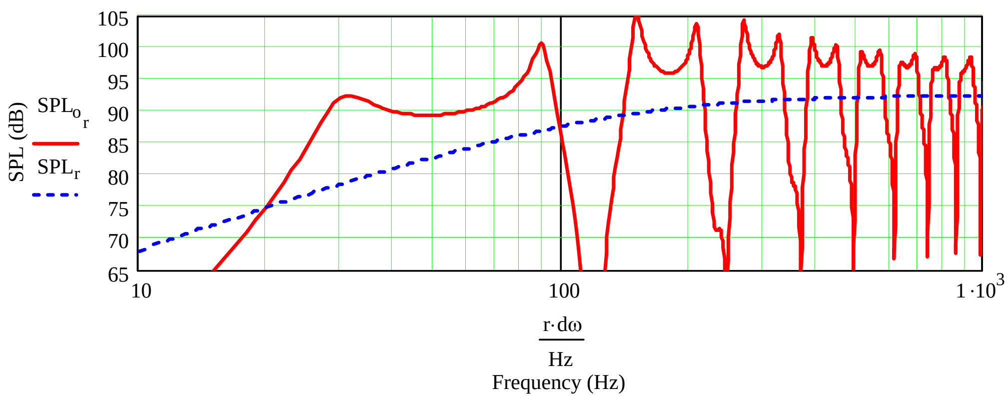
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

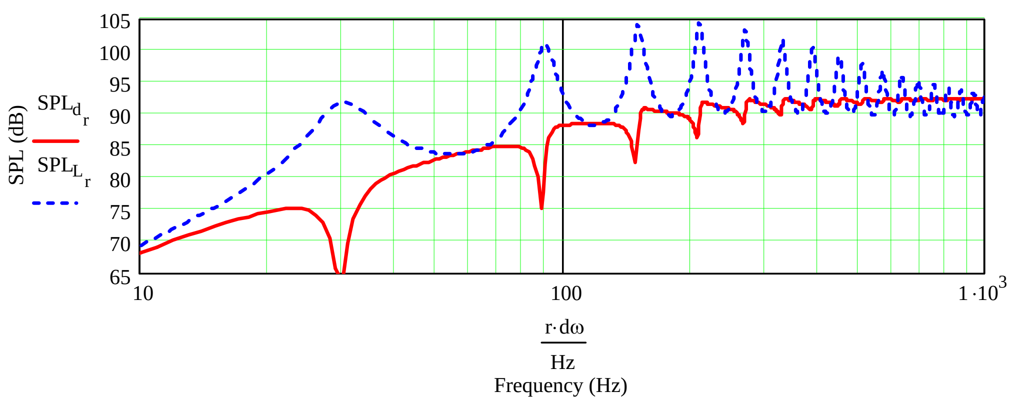


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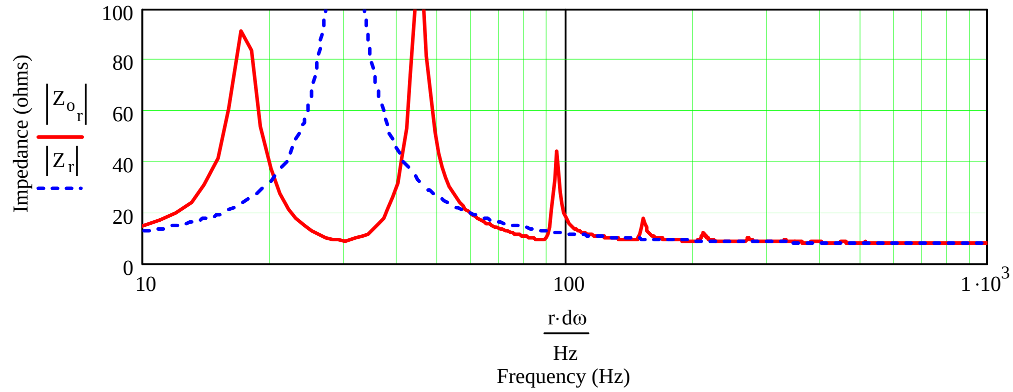
Figure A-2 : Generic Driver in a Straight Unstuffed Transmission Line

Q_{ts} = 0.3

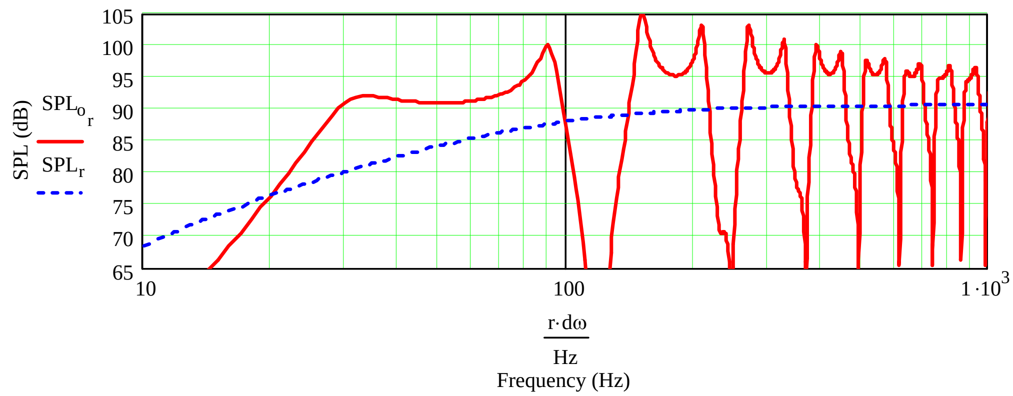
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

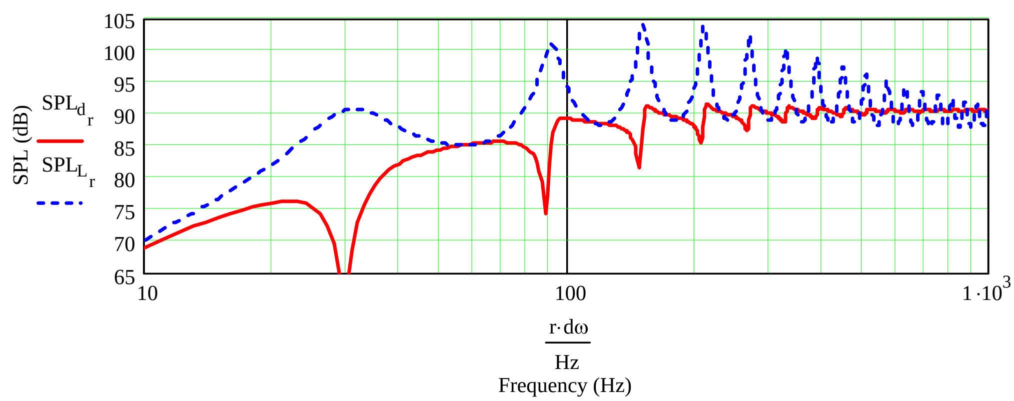


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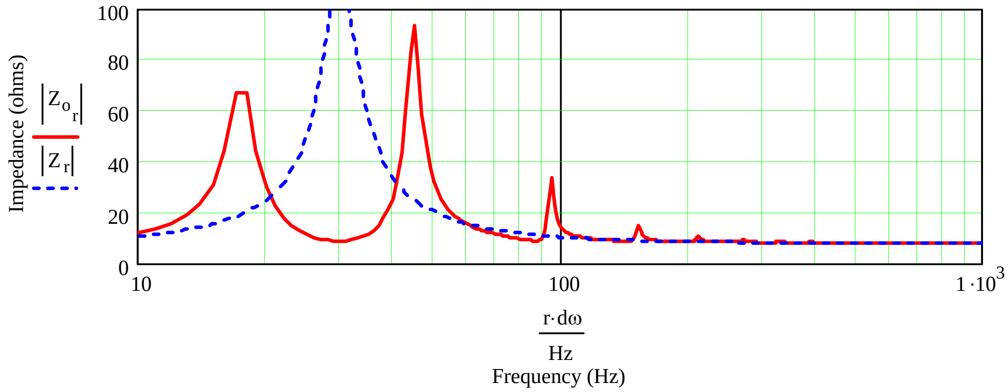
Figure A-3 : Generic Driver in a Straight Unstuffed Transmission Line
Q_{ts} = 0.4

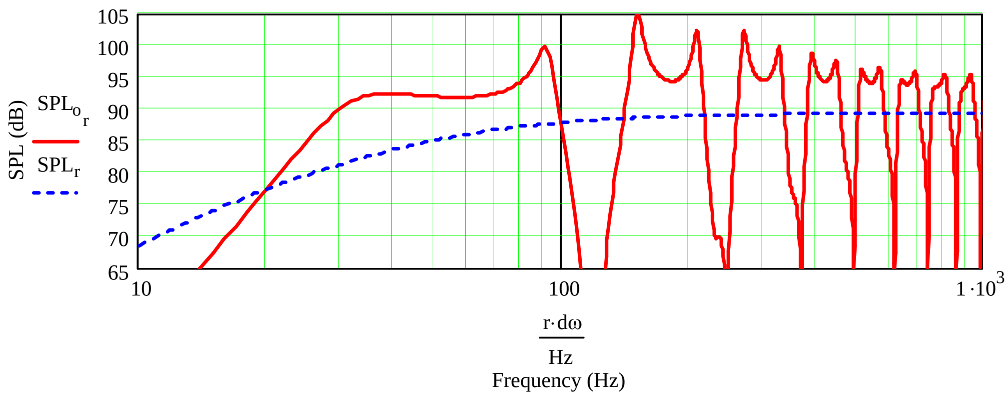
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

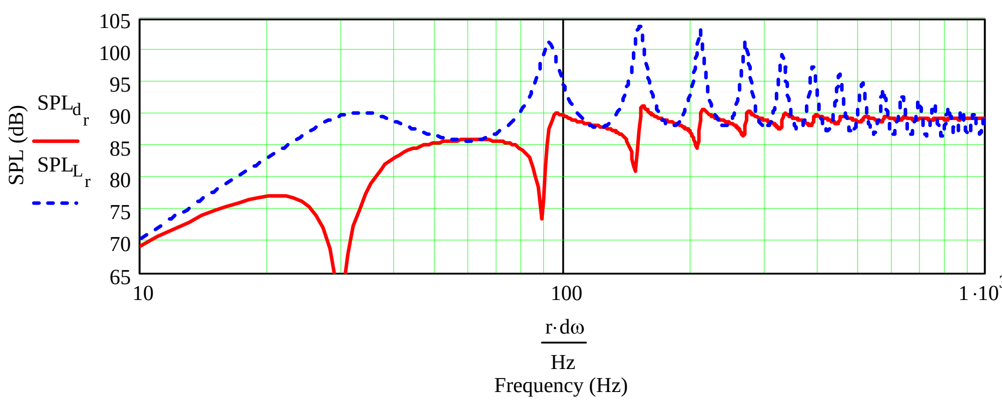


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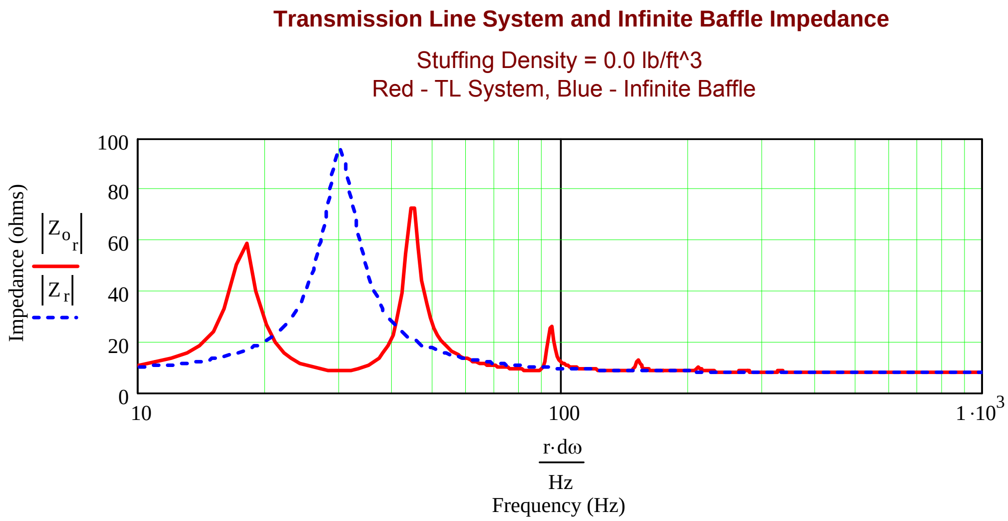
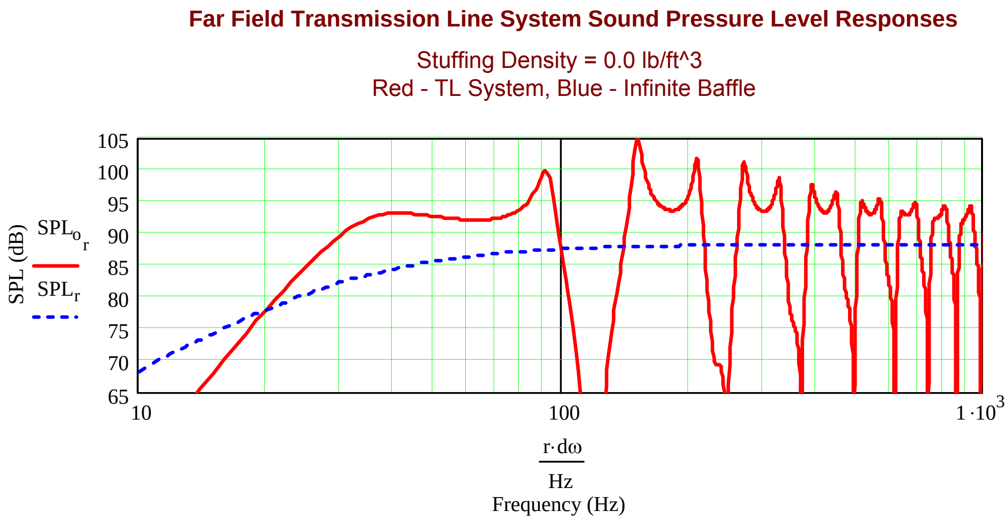
Figure A-4 : Generic Driver in a Straight Unstuffed Transmission Line
Q_{ts} = 0.5





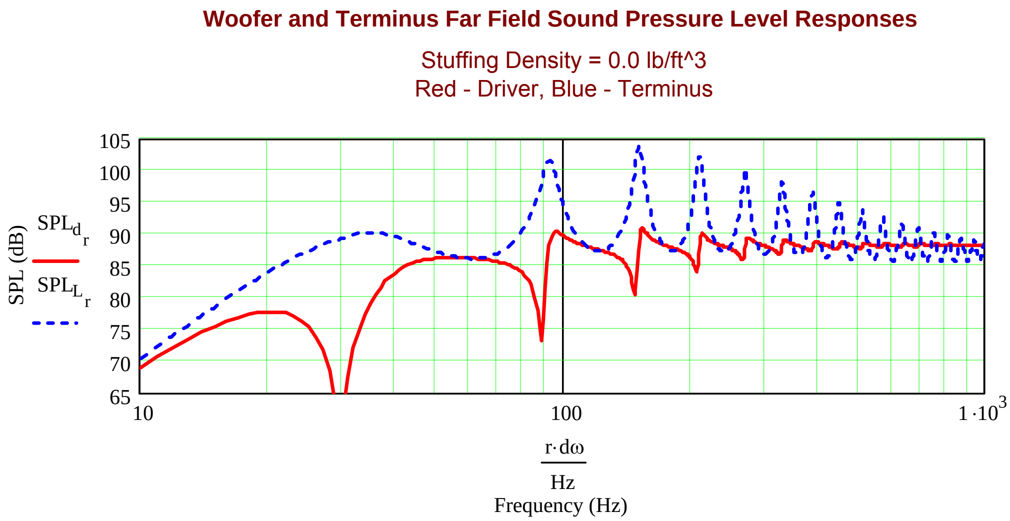


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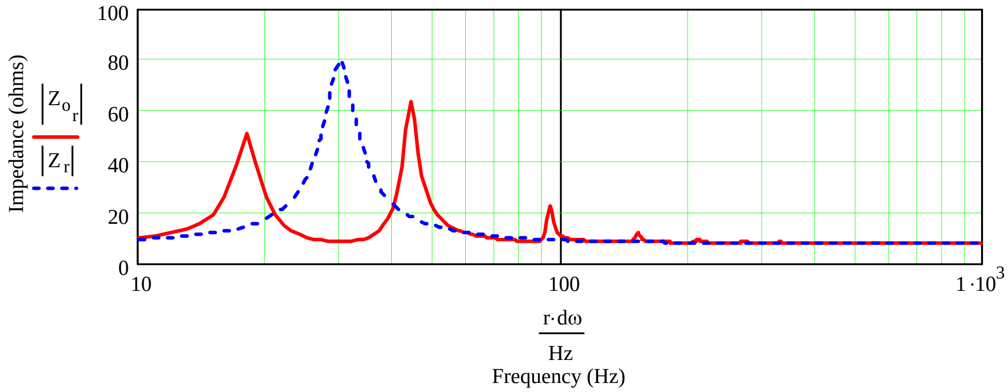
Figure A-5 : Generic Driver in a Straight Unstuffed Transmission Line
Q_{ts} = 0.6

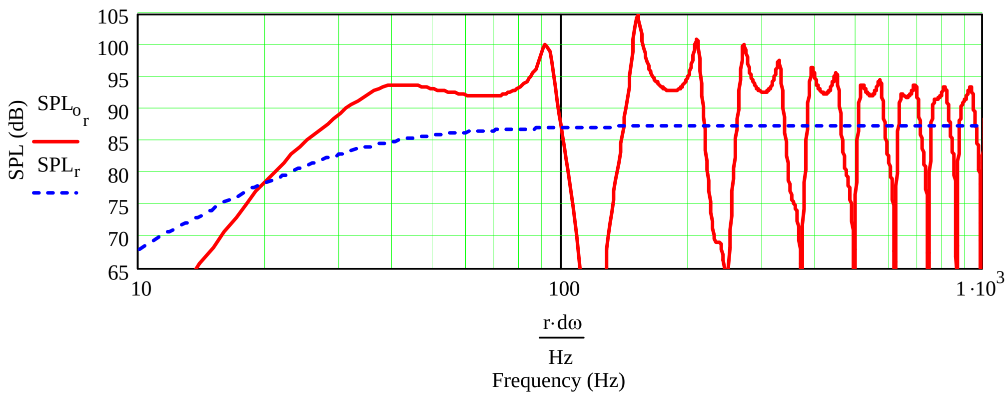
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

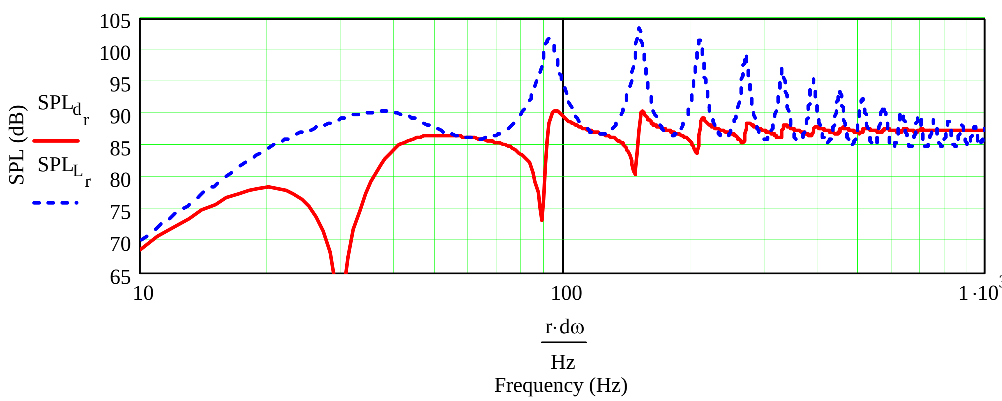


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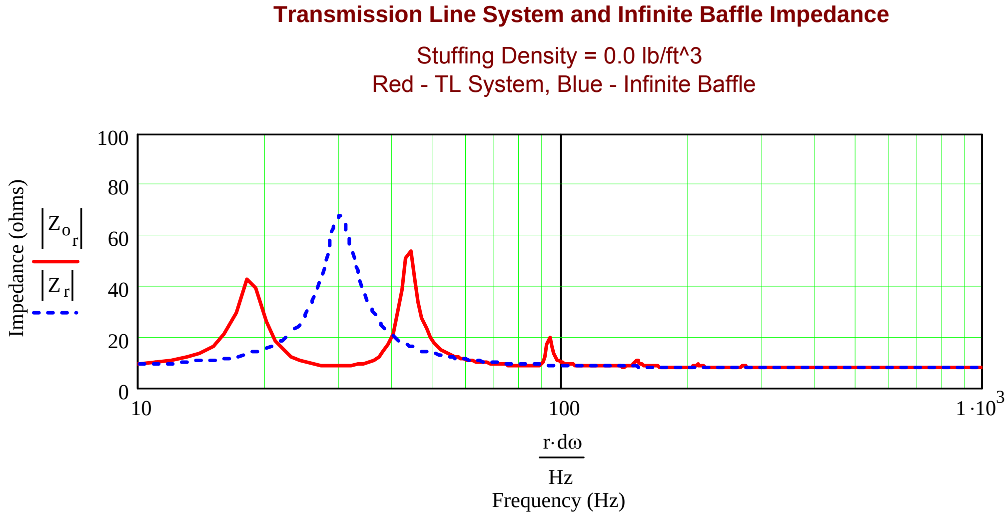
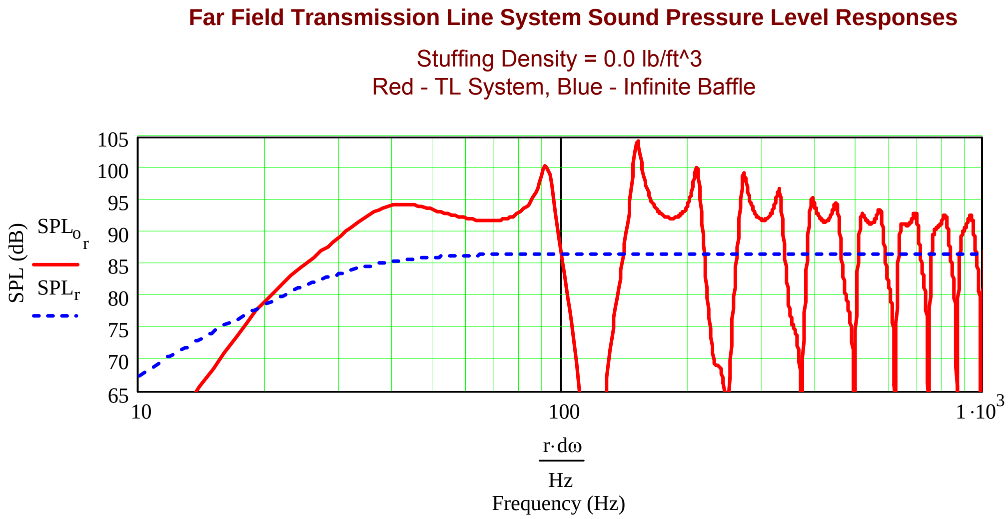
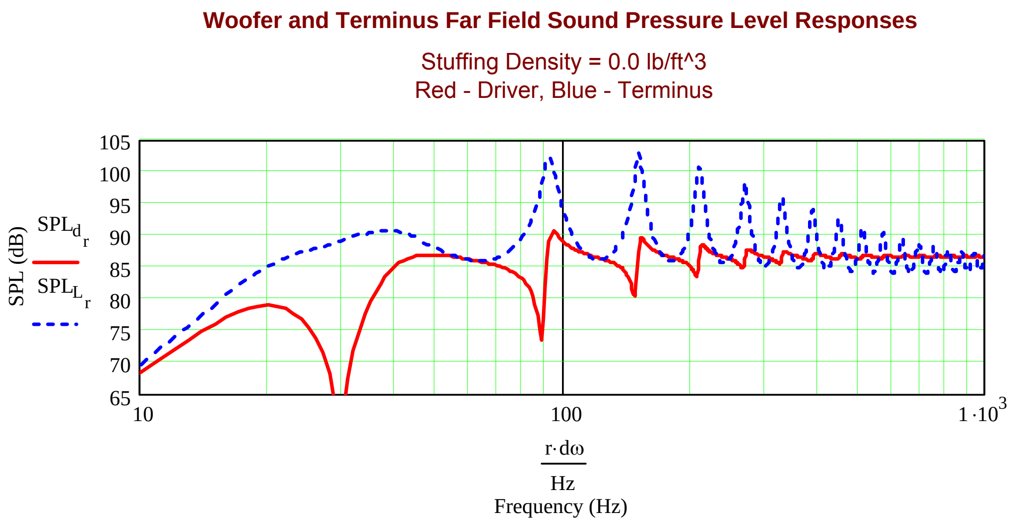
Figure A-6 : Generic Driver in a Straight Unstuffed Transmission Line
Q_{ts} = 0.7







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Attachment B : Transmission Line Response as a Function of Driver Position

Table 4 of the alignment tables lists the maximum recommended driver offset in the transmission line as a function of S_L/S_0. If the driver is placed at the closed end of the transmission line, all of the quarter wavelength resonances will receive the maximum excitation. Offsetting the driver along the length of the line reduces the amount of excitation applied to each of these resonances. The driver should be placed in the transmission line between the closed end and the maximum recommended offset show in Table 4.

To illustrate this behavior, a generic driver and transmission line geometry corresponding to the column in Attachment A for a Q_{ts} value of 0.4 is modeled with the driver at three different axial positions. The transmission line contains 0.5 lb/ft^3 of fiber stuffing for the first 2/3 of the length. The last 1/3 of the transmission line length is empty. Figure B-1 shows the calculated response with the driver at the closed end of the transmission line. Figures B-2 and B-3 show the calculated response with the driver offset in the transmission line so that ξ = 0.2 and ξ = 0.349 respectively.

In Figure B-1, it is easy to see in the middle graph that all of the resonances have been excited resulting in a rippled SPL response above 70 Hz. Offsetting the driver to ξ = 0.2, as shown in Figure B-2, does not eliminate the ripple but it does reduce the range in the system response (middle graph, red graph). Offsetting the driver to ξ = 0.349, as shown in the plots in Figure B-3, eliminates the second resonance and every other resonance above this point. But offsetting the driver to ξ = 0.349 does not reduce the magnitude of the ripple in the system response (middle graph, red curve) as much as ξ = 0.2.

It is also clear from these three Figures that bass response extension decreases as the offset increases. It is up to the speaker designer to trade off the amount of ripple in the design against the bass response extension. Unfortunately, there is no perfect solution.

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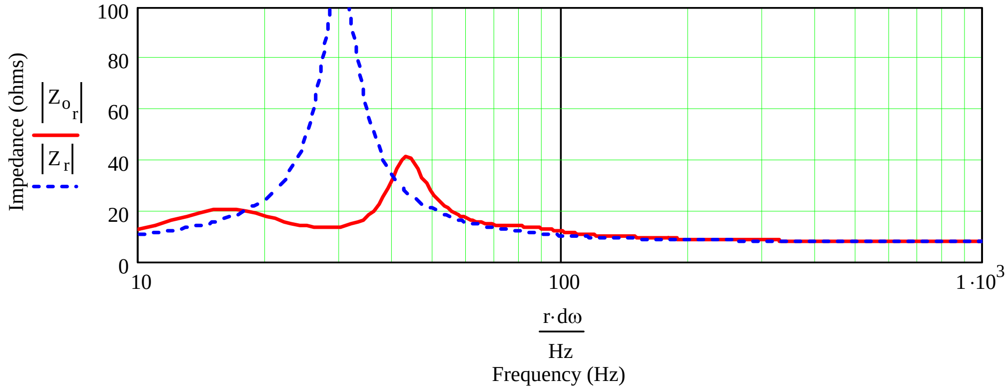
Figure B-1 : Generic Driver in a Straight Transmission Line

$\xi = 0$

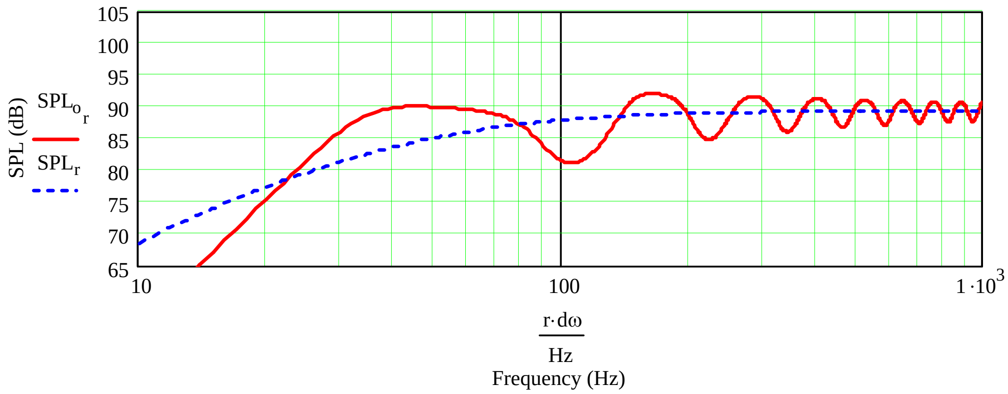
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - Driver, Blue - Terminus

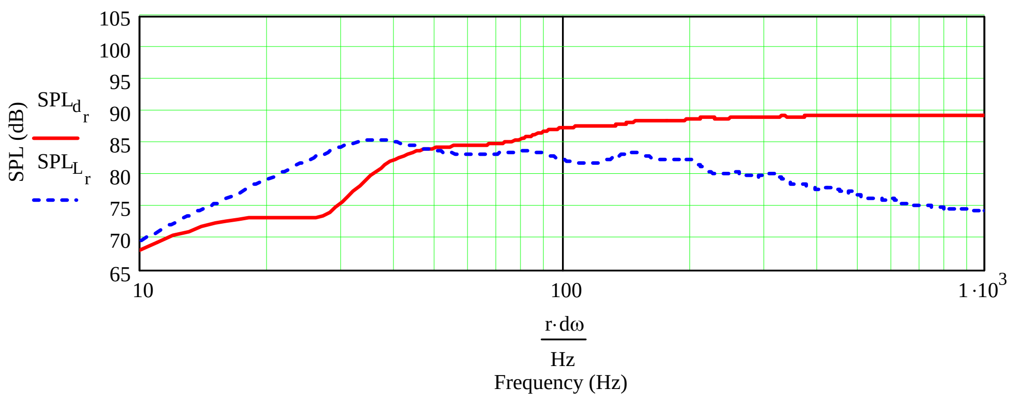


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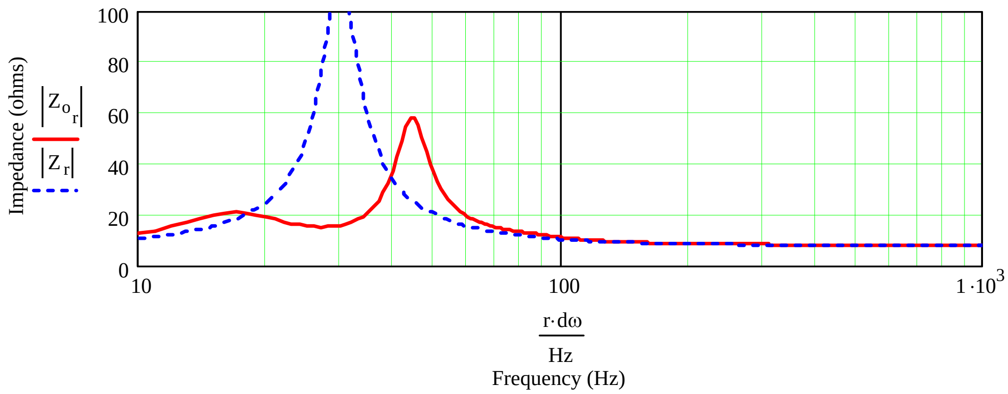
Figure B-2 : Generic Driver in a Straight Transmission Line
$\xi = 0.2$

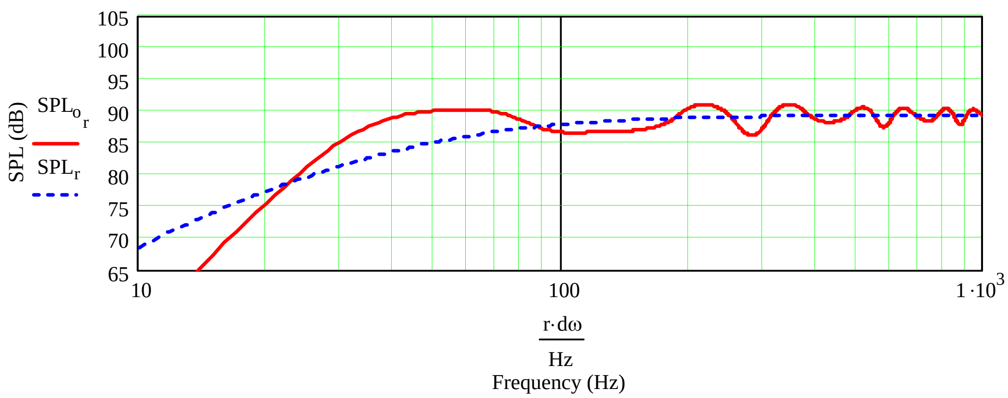
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - Driver, Blue - Terminus

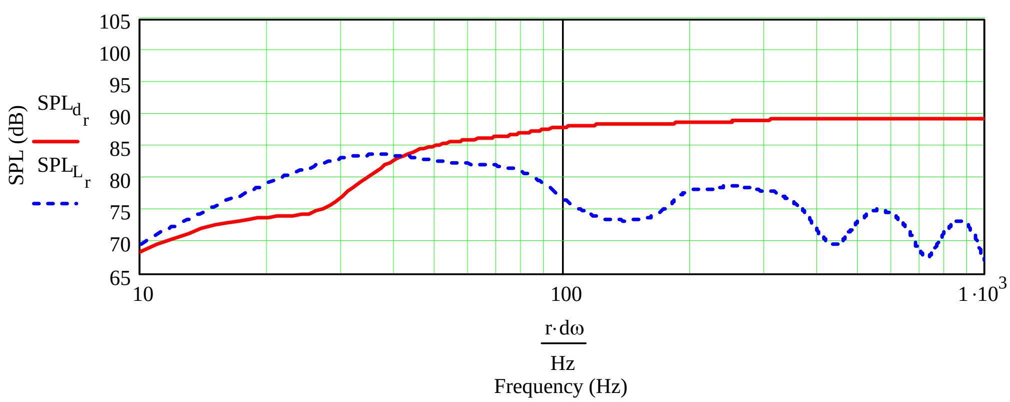


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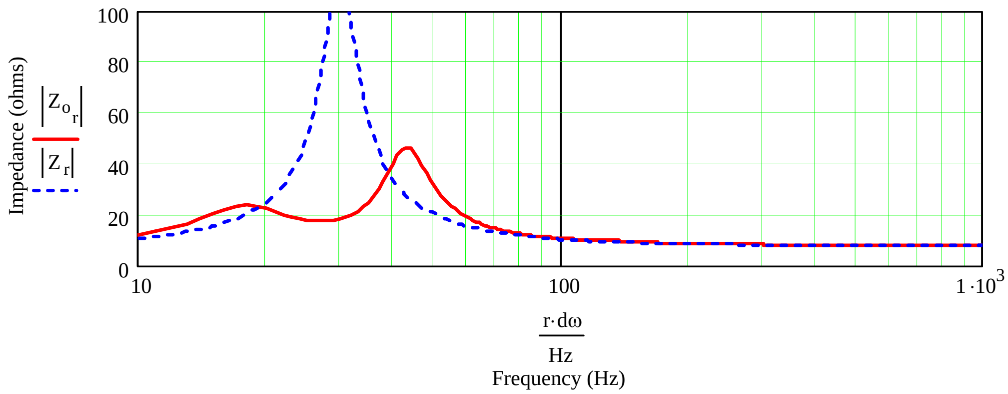
Figure B-3 : Generic Driver in a Straight Transmission Line
ξ = 0.349

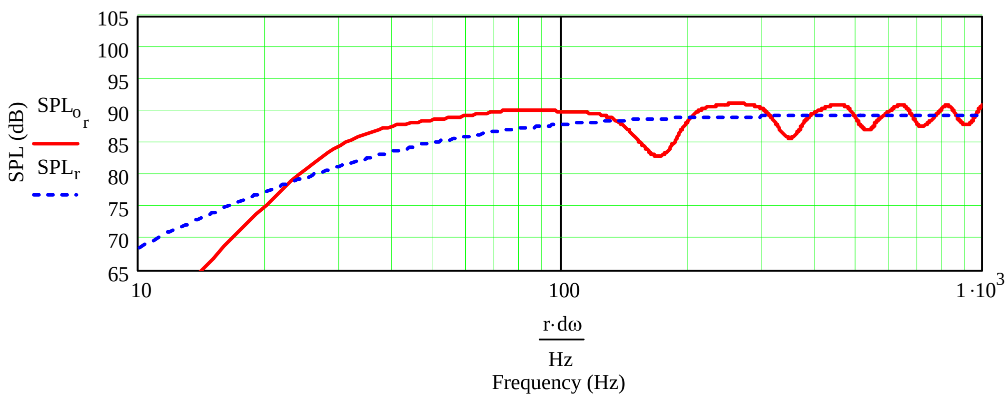
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



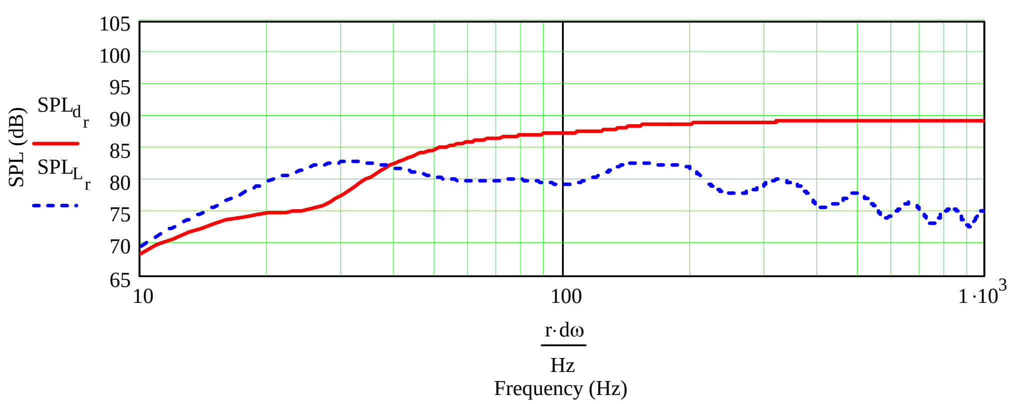
Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - Driver, Blue - Terminus



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Attachment C : Transmission Line Response as a Function of Enclosure Shape

To illustrate the response of a generic driver in different shaped transmission lines, the alignment tables were used to determine the line lengths and the cross-sectional areas associated with S_L/S_0 values of 0.1, 1.0, and 10.0. Again, the generic driver corresponding to the column in Attachment A for a Q_{ts} value of 0.4 was used in the simulations. Table C-1 summarizes the different alignment geometries. Note that the transmission line tuning frequency for all three geometries is 30 Hz.

Table C-1 : Transmission Line Geometry

Geometry	S_L/S_0 = 0.1	S_L/S_0 = 1.0	S_L/S_0 = 10.0	Units
Length	1.716	2.766	3.925	(m)
S_0/S_d	5.012	2.669	0.603	--
S_L/S_d	0.501	2.669	6.034	--

Figures C-1, C-2, and C-3 show the simulation results calculated using the MathCad worksheet "TL Open End" for S_L/S_0 values of 0.1, 1.0, and 10.0 respectively. There are several interesting observations that can be made about the data presented in these Figures.

1. Repeating what was stated in the previous paragraph, look at the differences in the line lengths in Table C-1 as S_L/S_0 varies from 0.1 to 10.0. All three of these designs are tuned to 30 Hz but the required transmission line lengths are drastically different.
2. Comparing the terminus outputs (bottom graph, blue curve), the tapered design does a much better job of damping the higher harmonics compared to the straight and expanding enclosure designs.
3. The location of the higher transmission line modes is also worth noting. Remember the fundamental is at 30 Hz in all three designs. The second modes occur at approximately 130 Hz, 90 Hz, and 74 Hz for S_L/S_0 values of 0.1, 1.0, and 10.0 respectively. As S_L/S_0 decreases, the length gets shorter and the higher harmonics are more widely spaced. As S_L/S_0 increases, the length gets longer and the higher harmonics drop in frequency until they start to bunch up. This is the reason for elevated average responses of TQWT, S_L/S_0 > 1.0, enclosures.
4. The tapered design, S_L/S_0 = 0.1, produces a nice compact enclosure with a very uniform bass response. Using just the alignment tables, a tapered transmission line enclosure appears to be the design with the highest potential for success. Using the alignment tables to produce an expanding transmission line or TQWT design appears to be a very high risk design option.

The degree of taper or expansion of the transmission line geometry has a large impact on the length and the system response. If you are looking at using only the alignment tables, and not doing any further optimization with one of the MathCad worksheets, I recommend a tapered line, S_L/S_0 < 1.0, design. If you want to be a little more aggressive and build a TQWT enclosure, then I would strongly recommend that you use the geometry derived from the alignment tables as input into the "TL Offset Driver" MathCad worksheets to optimize the driver location and the amount and distribution of fiber stuffing.

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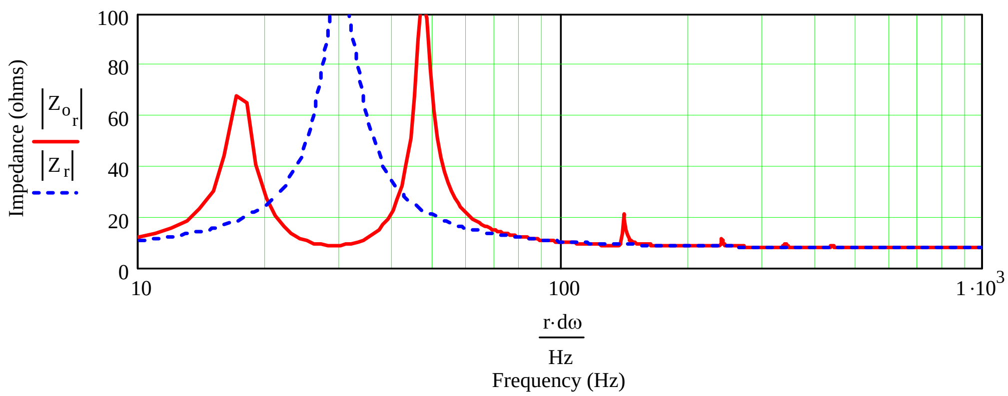
Figure C-1 : Generic Driver in a Tapered Transmission Line
$S_L/S_0 = 0.1$

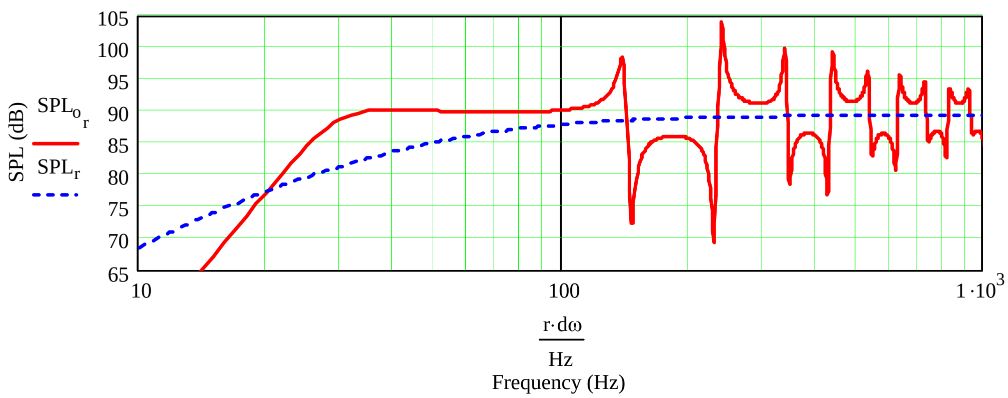
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

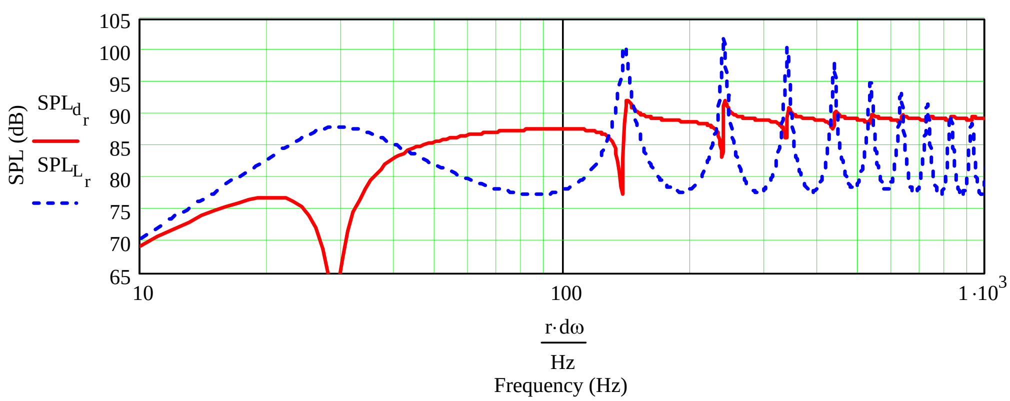


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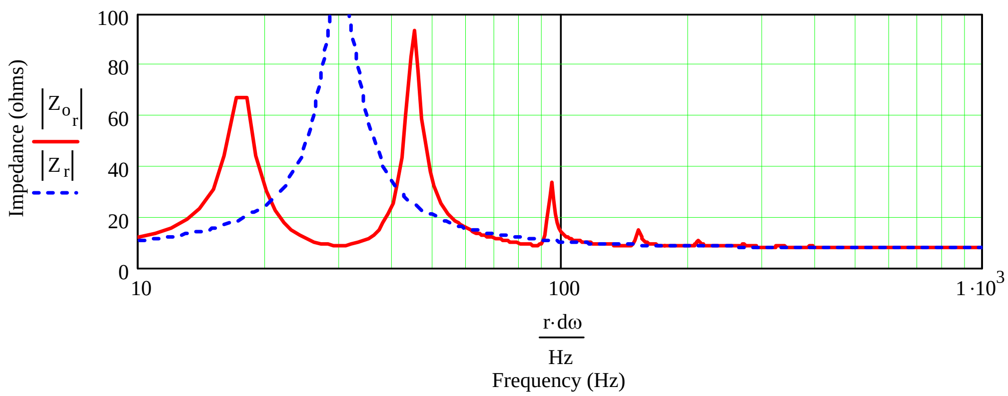
Figure C-2 : Generic Driver in a Straight Transmission Line
$S_L/S_0 = 1.0$

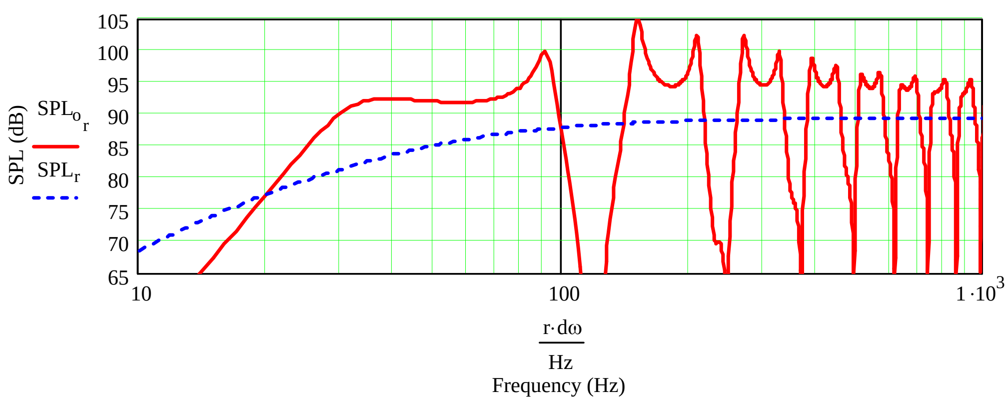
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

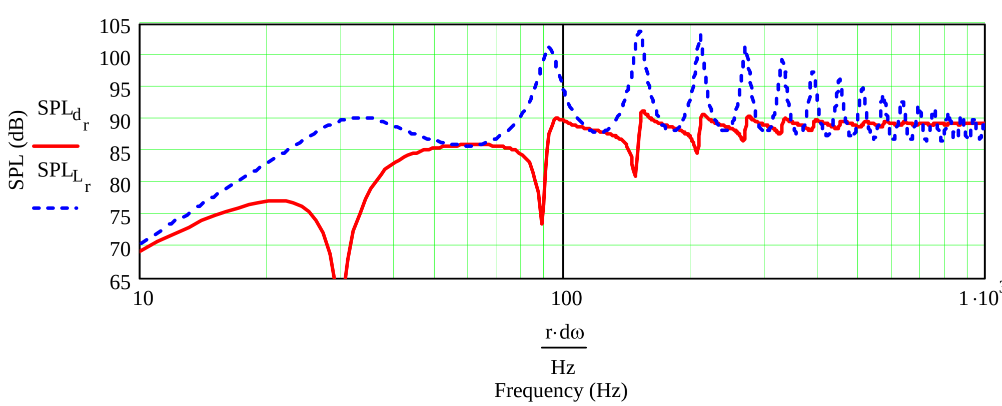


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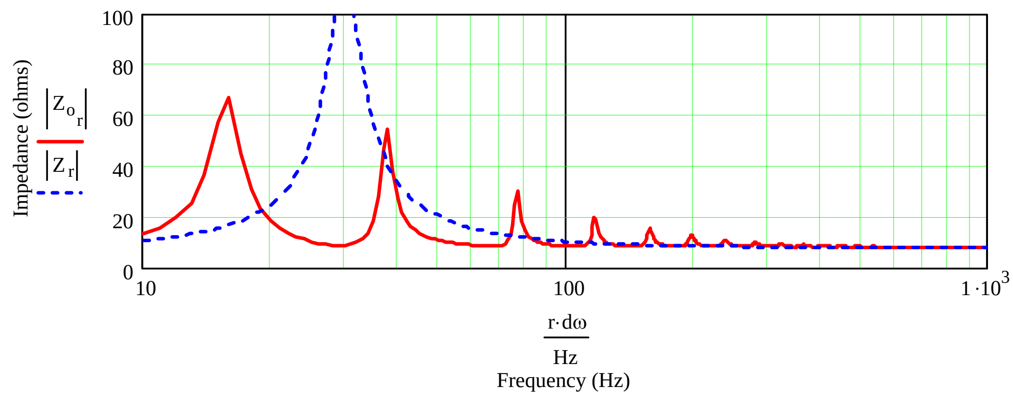
Figure C-3 : Generic Driver in a Expanding Transmission Line (or TQWT)
S_L/S_0 = 10.0

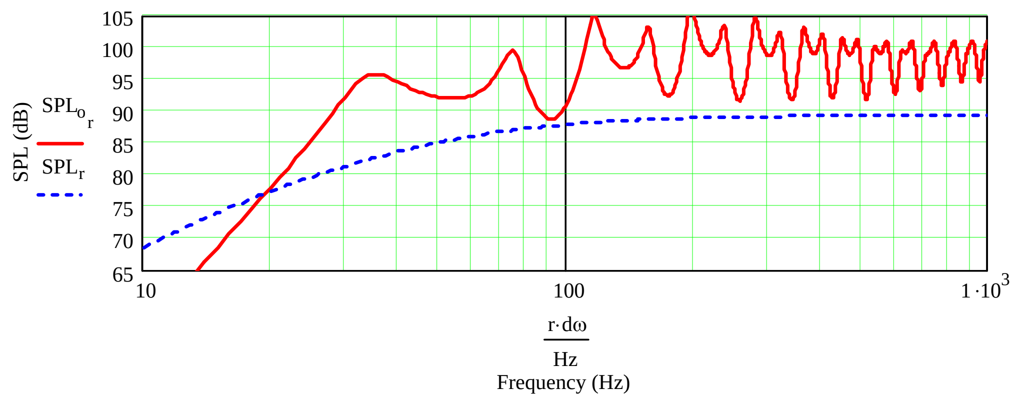
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



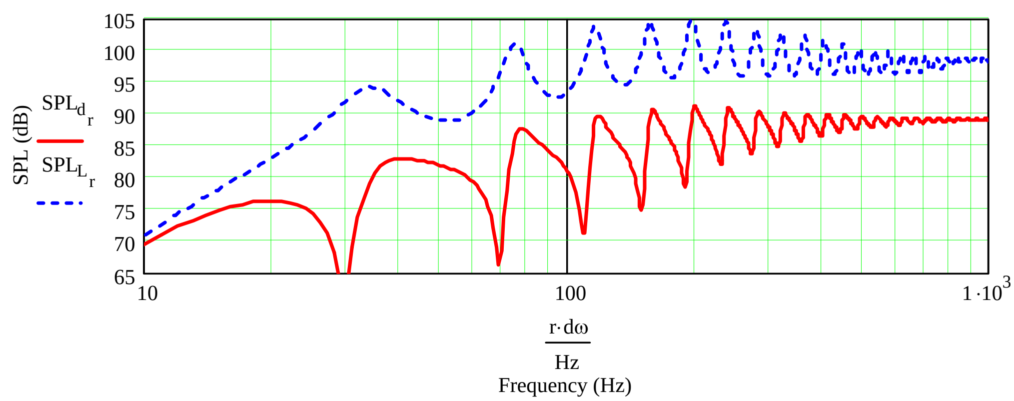
Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus



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Attachment D : Transmission Line Response as a Function of Stuffing Density

The final study is a set of simulations that show the impact of different densities of fiber stuffing on the transmission line's response. A generic driver and transmission line geometry, again corresponding to the column in Attachment A for a Q_{ts} value of 0.4, is modeled with four different stuffing densities. The transmission line contains fiber stuffing for the first 2/3 of the length. The last 1/3 of the transmission line length is empty. Figure D-1 shows the calculated response of the driver at the closed end of the transmission line without any stuffing. Figures D-2, D-3, D-4, and D-5 show the calculated response of the same transmission line with 0.25 lb/ft^3, 0.5 lb/ft^3, 0.75 lb/ft^3, and 1.0 lb/ft^3 stuffing densities respectively. There are several interesting observations that can be made about the data presented in these Figures.

1. Increasing the stuffing density decreases the ripple but at the same time attenuates the lowest bass response.
2. The double humped impedance curve (top graph, red curve) produced by the empty transmission line, is also damped by the stuffing. In particular, as stuffing density increases the first impedance peak is highly damped and can even flatten out leaving what appears to be a single hump impedance curve.
3. The bass roll-off rate of 24 dB/octave, below the tuning frequency, which is obvious in the empty transmission line system SPL response (middle graph, red curve), has become rolled off as fiber damping is added. The transition is slower between the pass band and the eventual 24 dB/octave low frequency roll off rate.

The second and third observations are the source of repeated discussions on various DIY forums. Purists argue that the classic stuffed transmission line behaves just like a critically damped, Q_{tc} = 0.5, sealed box. They point to the single hump in the impedance curve and the gradual roll-off (~12 dB/octave) around the system tuning frequency. Hopefully the Figures in this Attachment demonstrate the natural impedance of a transmission line, double humped, and the influence of the fiber damping on the SPL and impedance curves.

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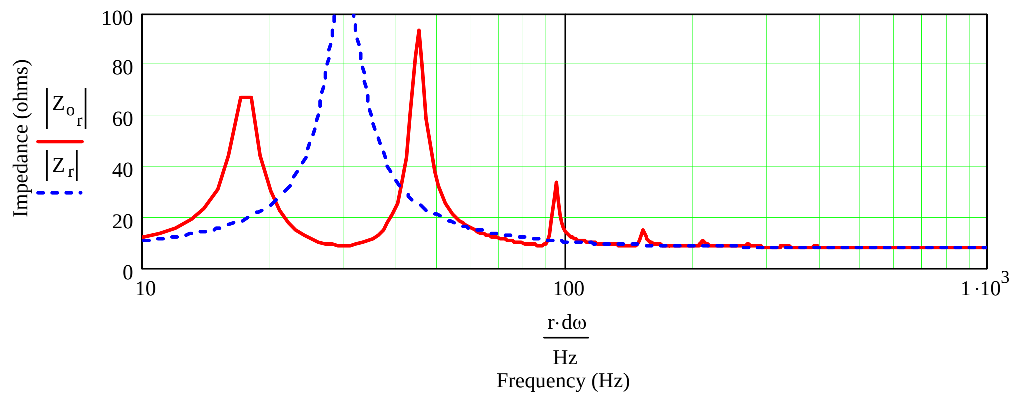
Figure D-1 : Generic Driver in a Straight Transmission Line
Density = 0.0 lb/ft^3

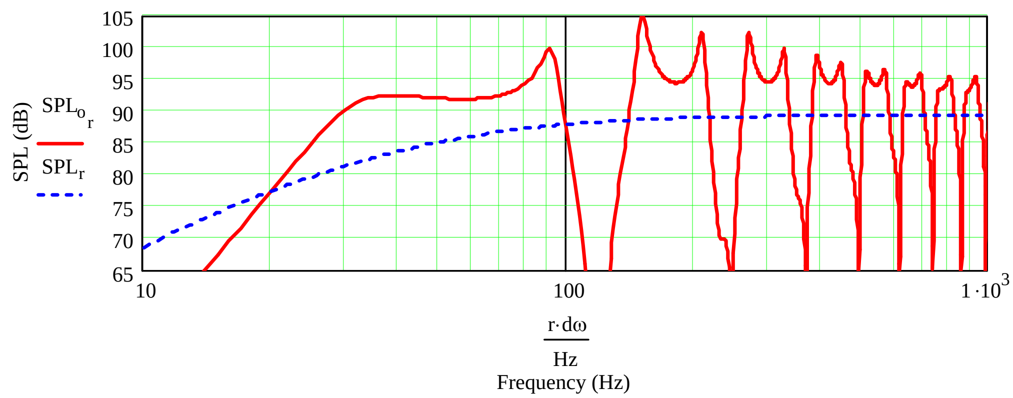
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.0 lb/ft^3
Red - Driver, Blue - Terminus

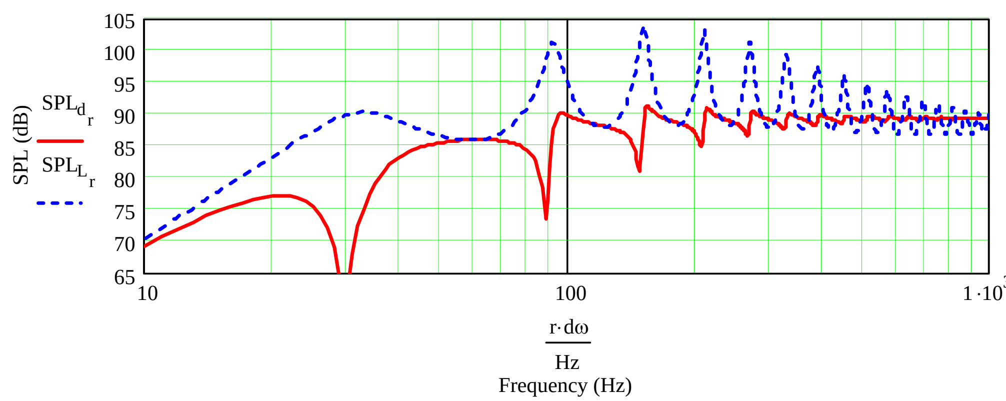


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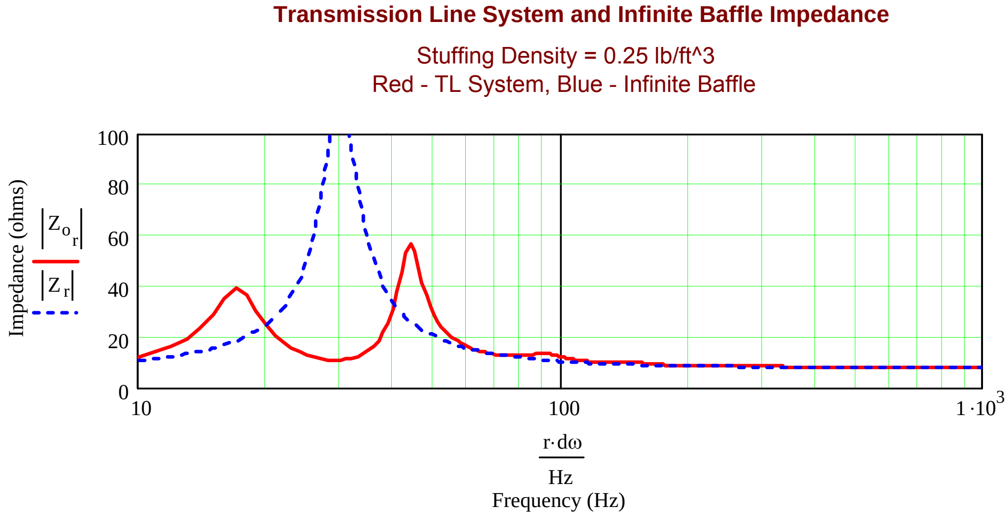
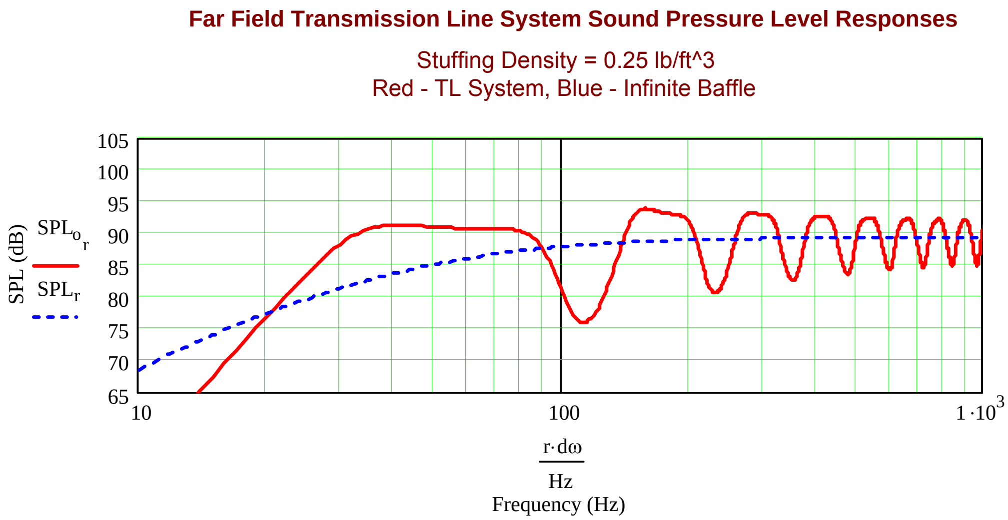
Figure D-2 : Generic Driver in a Straight Transmission Line
Density = 0.25 lb/ft^3





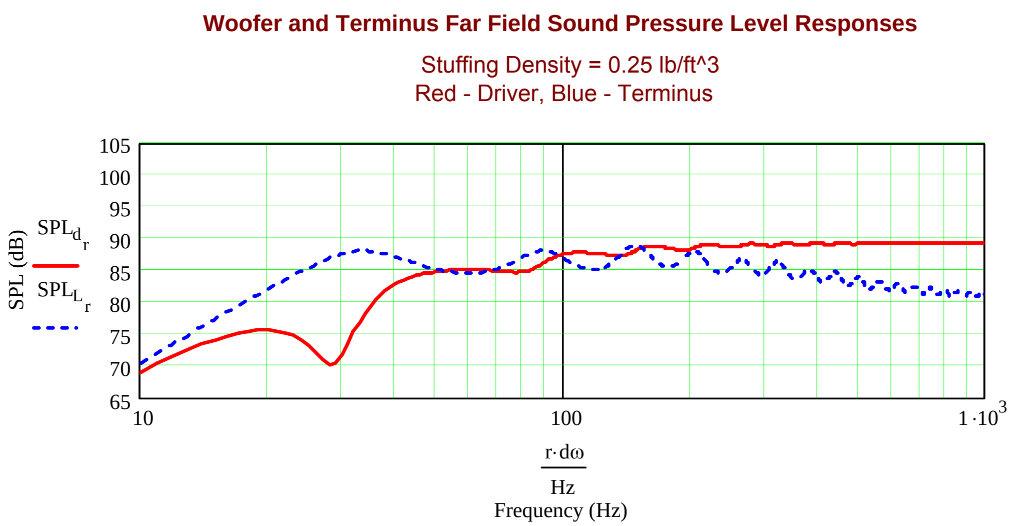


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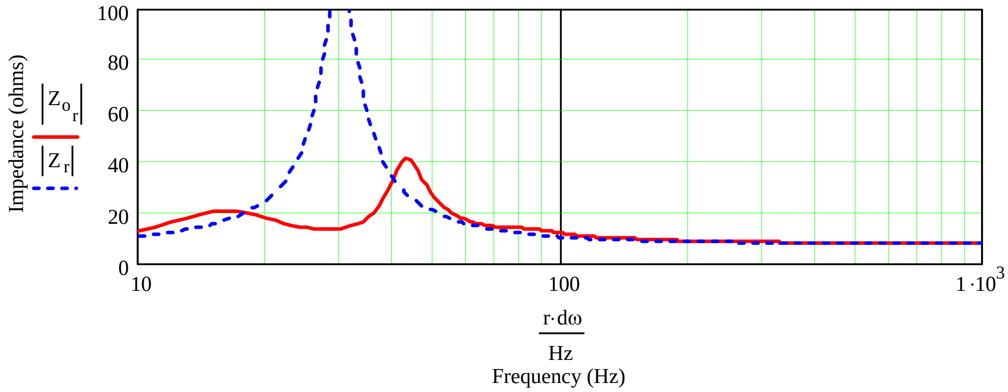
Figure D-3 : Generic Driver in a Straight Transmission Line
Density = 0.5 lb/ft^3

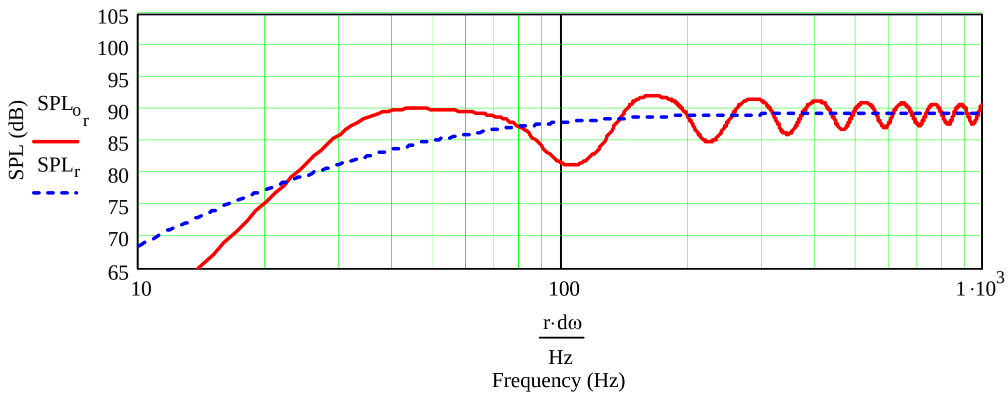
Transmission Line System and Infinite Baffle Impedance

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Far Field Transmission Line System Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - TL System, Blue - Infinite Baffle



Woofer and Terminus Far Field Sound Pressure Level Responses

Stuffing Density = 0.5 lb/ft^3
Red - Driver, Blue - Terminus

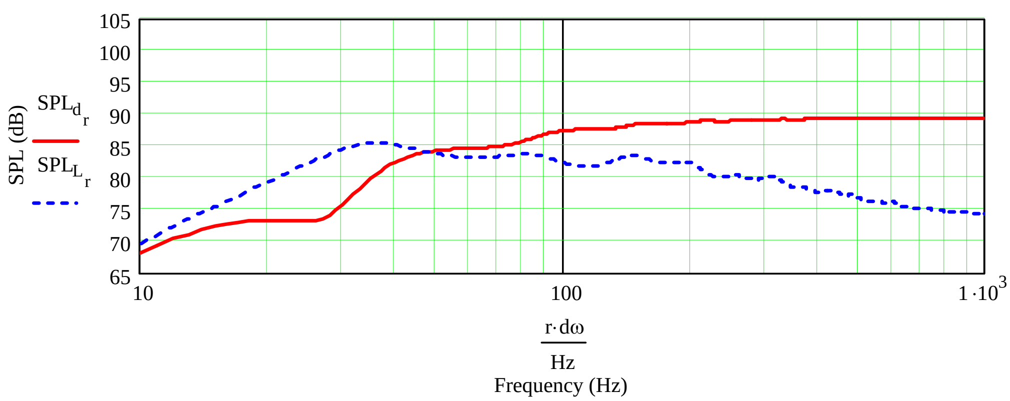


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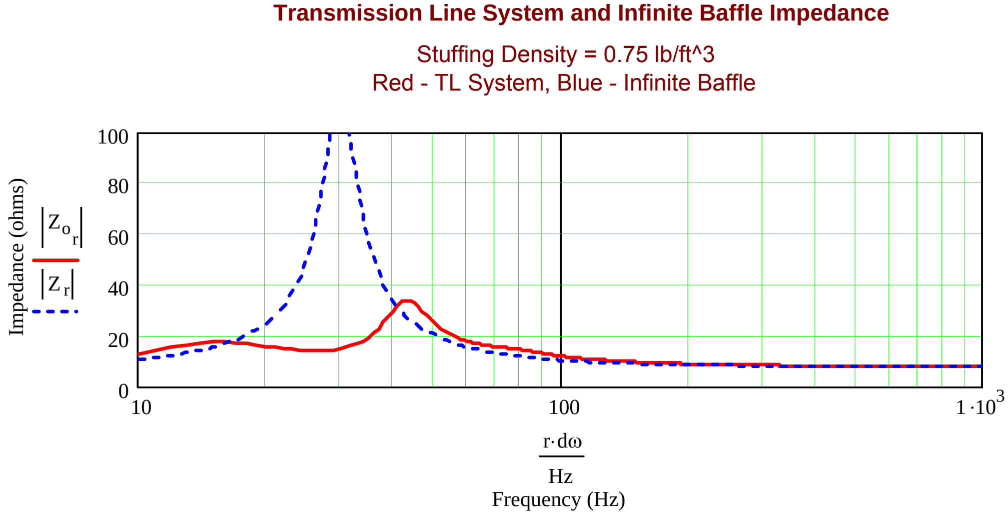
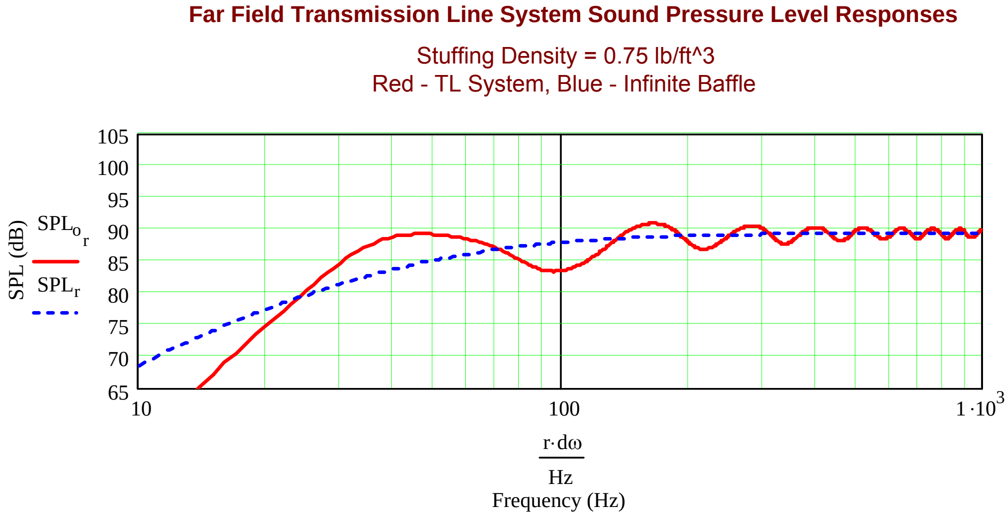
Figure D-4 : Generic Driver in a Straight Transmission Line
Density = 0.75 lb/ft^3





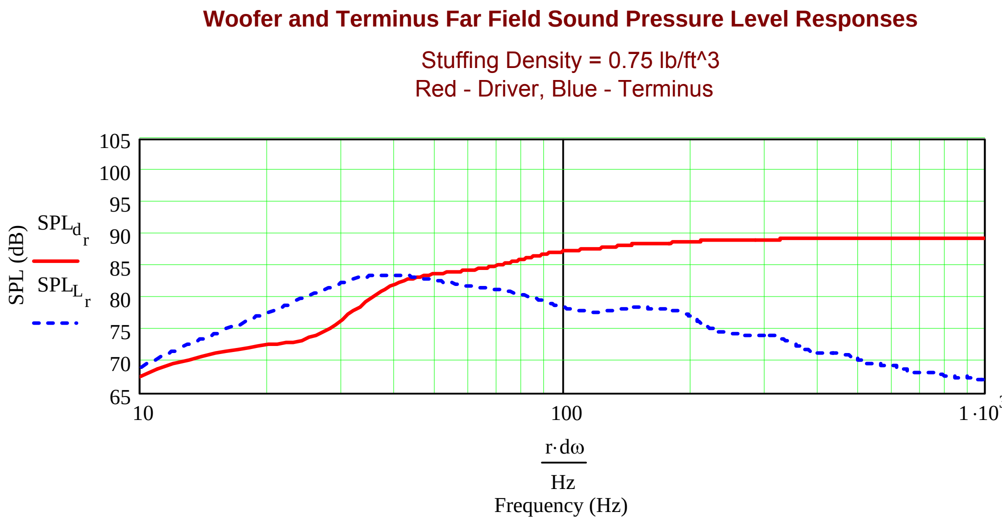


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Figure D-5 : Generic Driver in a Straight Transmission Line
Density = 1.0 lb/ft^3