Bass Reflex and Transmission Line Enclosure Performance

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Introduction

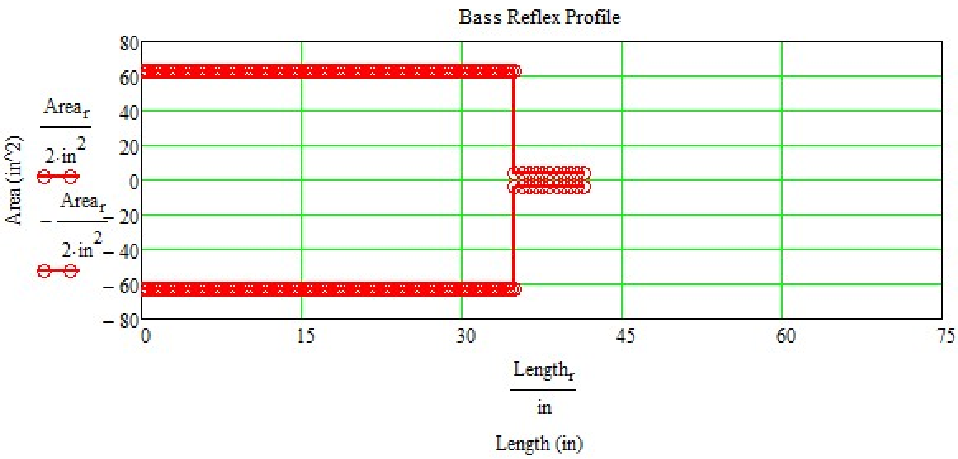
Bass Reflex (BR) and Transmission Line (TL) loudspeakers are both 4^{th} order acoustic systems with a 24 dB/octave roll off below the tuning frequency. A resonant driver is mated with a resonant enclosure, typically tuned close to the driver's f_s value, to produce deeper bass with less driver excursion compared to the same driver mounted in a sealed enclosure. A resonant driver in a sealed enclosure remains a 2^{nd} order acoustic system with a 12 dB/octave roll off below the tuning frequency which will always be above the driver's f_s value.

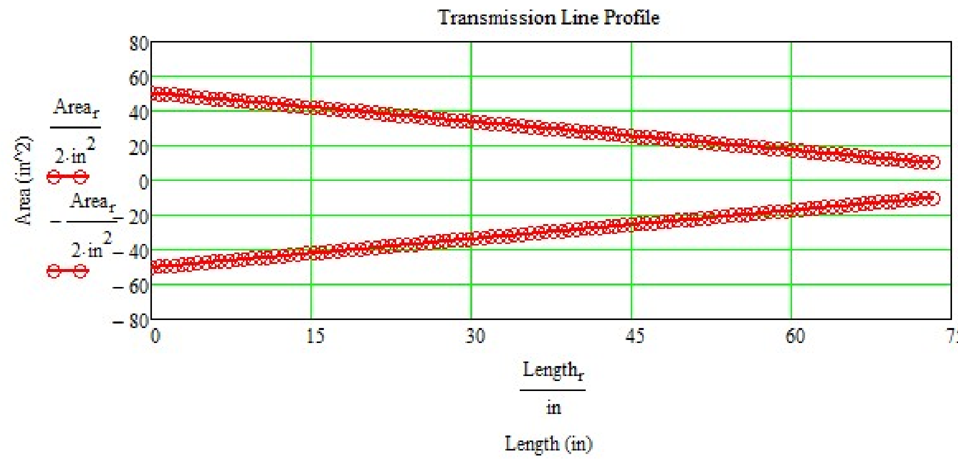
Bass Reflex speakers are very common (dominant) DIY and commercial designs while Transmission Line speakers are a less popular fringe design. There are many trade-offs between the two types of enclosures, a TL is a little more difficult to design due to the larger number of degrees of freedom available to the designer. The intent of this short presentation is to highlight what happens inside the two types of enclosures at the tuning frequency and show why a Transmission Line has a significant performance advantage over a Bass Reflex enclosure at these low frequencies.

First, please forgive me for using mixed measurement units. Some of the data on the following slides have English units, some have MKS units, and some have both. I was educated using English units (pounds, inches, seconds) but finished my career with a company using MKS units (kilograms, meters, seconds). I tend to fall back on the units I have a physical feel for which ends up as mixed units in my audio presentations. The results and conclusions will not change if I cleaned up my act and used consistent units, but my feel for the problem and solution would be compromised. Thankfully, MathCad keeps track of the units for me and performs all the calculations correctly.

You can drive any speaker to distortion with enough input voltage. A rule of thumb that I have seen used to design BR enclosure ports is to keep the RMS velocity in the port below 5% of the speed of sound (< 17 m/sec) to avoid unwanted port noises. The rational for this limit is the belief that the velocity (and calculated Reynold’s number) leads directly to turbulence and additional noisy artifacts. I have always struggled with the assertion that turbulent flow exists in a tube with an oscillating air column. But I will accept and apply this metric to compare BR and TL enclosure designs.

Definition of Equivalent BR and TL Speaker Systems



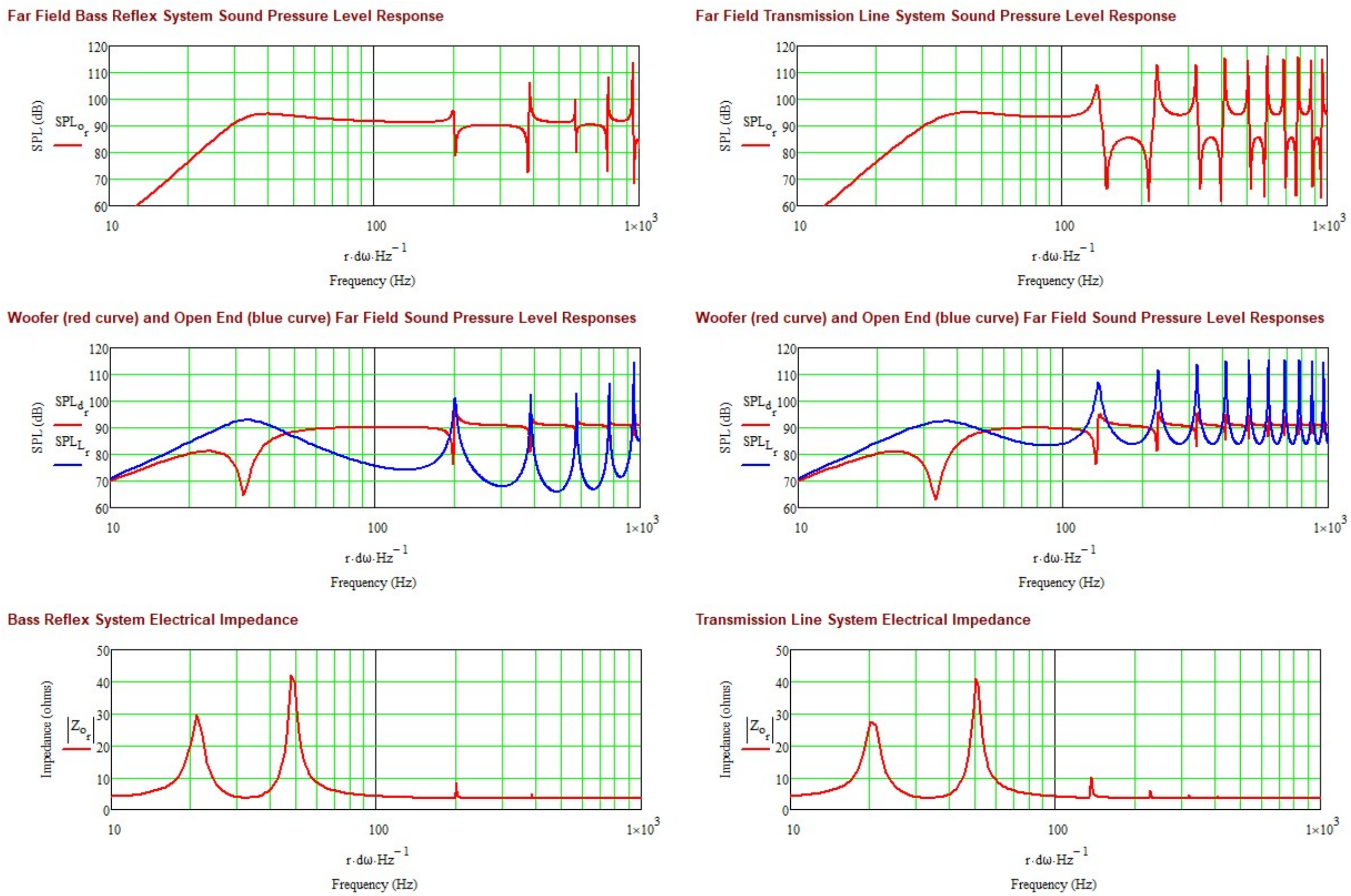


Equivalent BR and TL enclosures have the same internal volumes and tuning frequencies. The two enclosures shown above both have internal volumes of ~ 72.5 liters with tuning frequencies of 32-33 Hz. The driver used in the simulations is the Satori WO25P-4 woofer.

For this example, the driver is located at the closed end (no offset), internal damping material has been removed, and the acoustic boundary condition at the open ends have been set to p(L) = 0 and d (u(L)) / dx = 0 for simplicity. These conditions will maximize the pressure p and volume velocity U responses when plotting the standing waves in the enclosures.

Pressure p and volume velocity U (= Area x velocity u) are the variables used in acoustic analyses of loudspeaker enclosures. These are the mode shape variables that will be plotted. The actual air velocity u and displacement x will be derived from the volume velocity U. The values plotted are all RMS where the actual oscillating magnitude is +/- 1.414 times the RMS value.

Calculated SPL and Electrical Impedance Responses

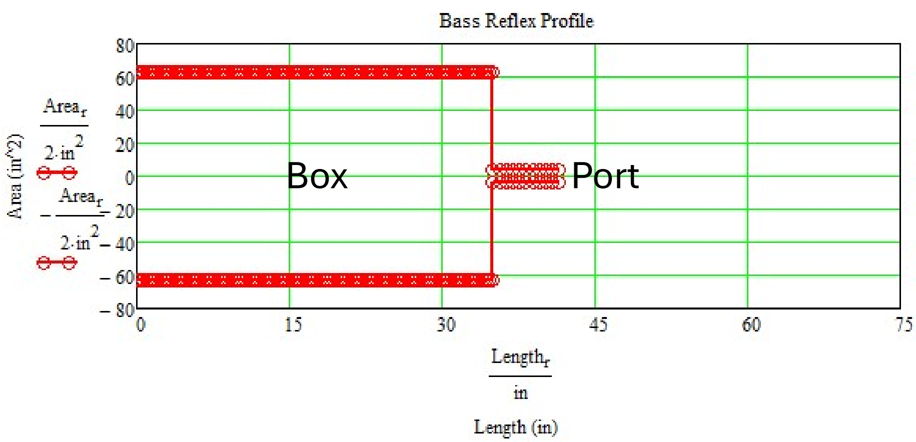


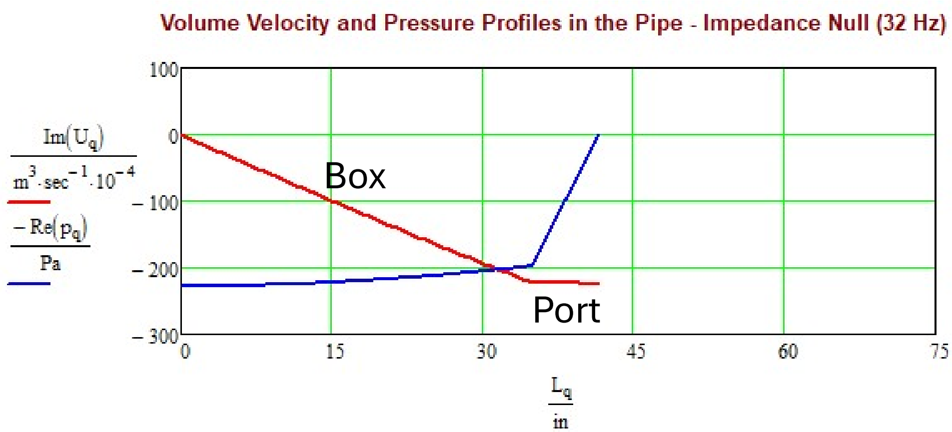
The SPL response plots show the infinite baffle results with the driver and open end, or port, assumed to be coincident. Both produce SPL output between 92-93 dB/m/2.8284 volts at 100 Hz. These assumption are consistent with almost all simple freeware speaker design programs.

Multiple higher frequency resonances occur in both the BR (left) and TL (right) plots. Most freeware programs do not show these higher resonances in BR enclosures; this is a limitation of the lumped parameter modeling used in the software.

Without knowing the enclosure geometry, it would be difficult to differentiate between a BR and a TL response based only on either of these sets of results.

Volume Velocity and Pressure Profiles in the BR Enclosure at the Tuning Frequency



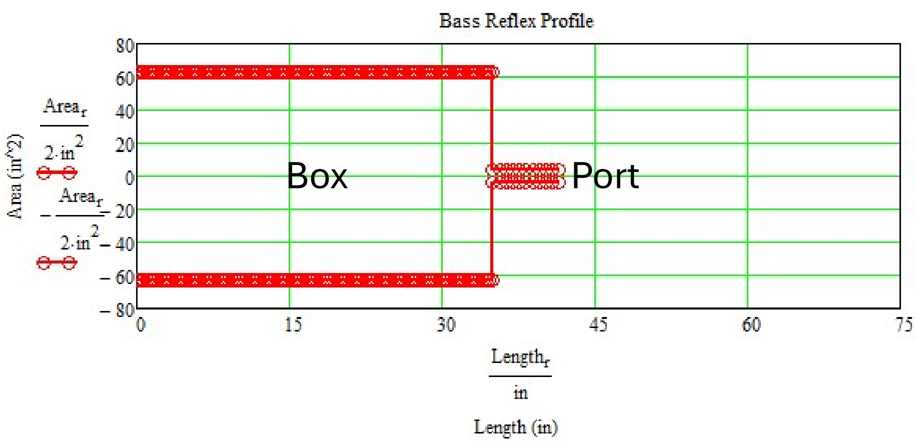


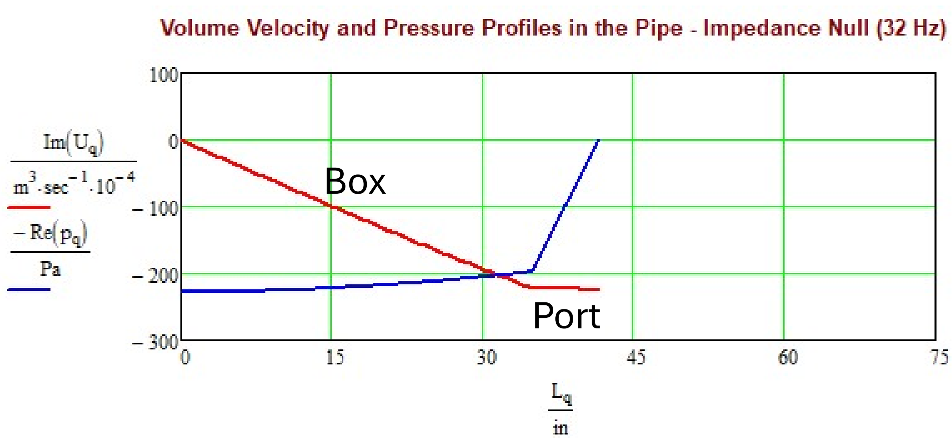
At left are plots showing the BR geometry and the RMS pressure p (blue) and RMS volume velocity U (red) along the length of the enclosure at 32 Hz. For a 1D model the relationship between pressure and volume velocity is :

$$- \partial p(x) / \partial x = j \omega \rho u(x)$$

where $u(x) = U(x) / Area$

In both curves a sharp discontinuity exists where the box ends and the port begins. The pressure in the box is almost constant and then rapidly decreases to zero along the length of the port. The slowly decreasing pressure in the box generates a small increasing volume velocity moving from the closed end to the port. The steep linear decrease in pressure along the port's length yields a maximum constant volume velocity. This is consistent with lumped parameter modeling of a BR enclosure.





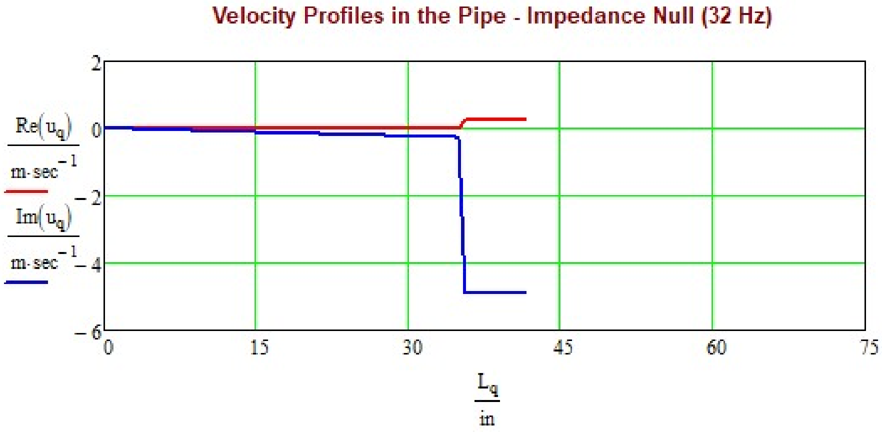
Plots of internal pressure and volume velocity are not commonly available for a BR or TL design. A lot can be learned from the shape of these plots as described below.

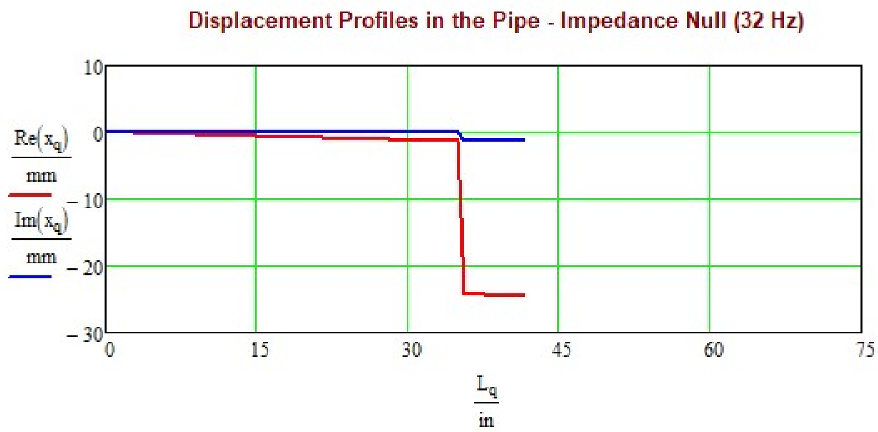
The RMS pressure at the closed end, on the back of the driver's cone, is 230 Pa which is equivalent to 141 dB. This corresponds to an RMS force on the driver's cone of 1.32 lbf, enough to stop the cone's motion at 32 Hz as seen in the left column's middle plot on slide 5.

For comparison at 32 Hz, the SPL/m/2.8284 is 92.7 dB corresponding to an RMS pressure of 0.863 Pa and RMS displacement of 1.031×10^{-2} mm. This is what your ear picks up as sound at 1 m on the woofer axis.

The pressure is compressive, meaning the air is moving into the enclosure. The volume velocity is zero at the closed end and decreases linearly (like a compressed linear spring) to the port before attaining a maximum constant value along the entire port tube.

Velocity and Displacement Profiles in the BR Enclosure at the Tuning Frequency



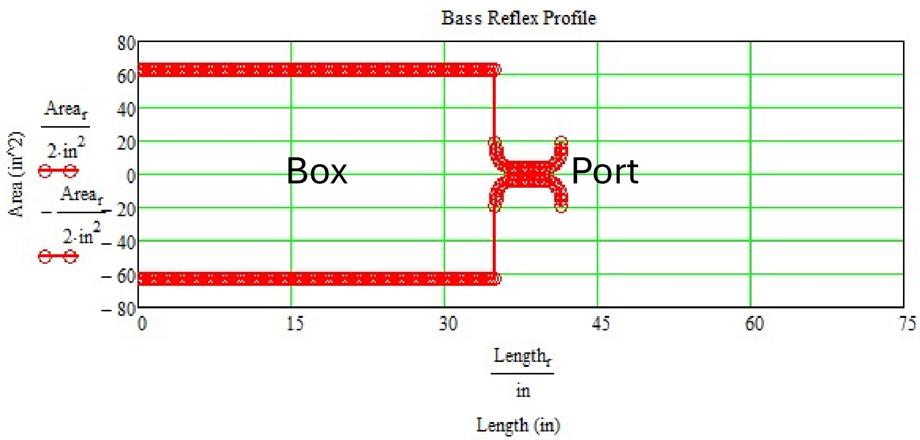


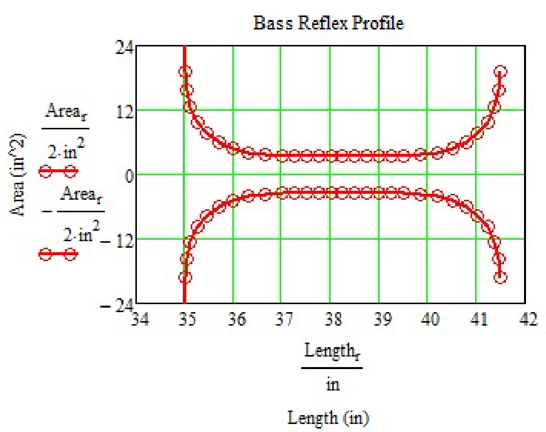
Dividing the volume velocity by the cross-sectional area produces the velocity in the top plot. Real (red) and Imaginary (blue) curves are shown representing magnitude and phase (which is almost zero). Integrating the velocity plot with respect to time, dividing by frequency, yields the displacement in the bottom plot. These are both still RMS values at 32 Hz.

In this example the port's RMS velocity is about 5 m/sec with an RMS displacement of 24.4 mm for 2.8284 volts (1 watt into 8 ohms) input.

Increasing the voltage by a factor of 3.4 (12.25 watts at 32 Hz), the SPL at 1 m rises to 103.6 dB with an RMS velocity of 17 m/sec and an RMS displacement of 85 mm in the port. For the assumed metric on slide 2, this is the input limit imposed by this port design for acceptable linear behavior.

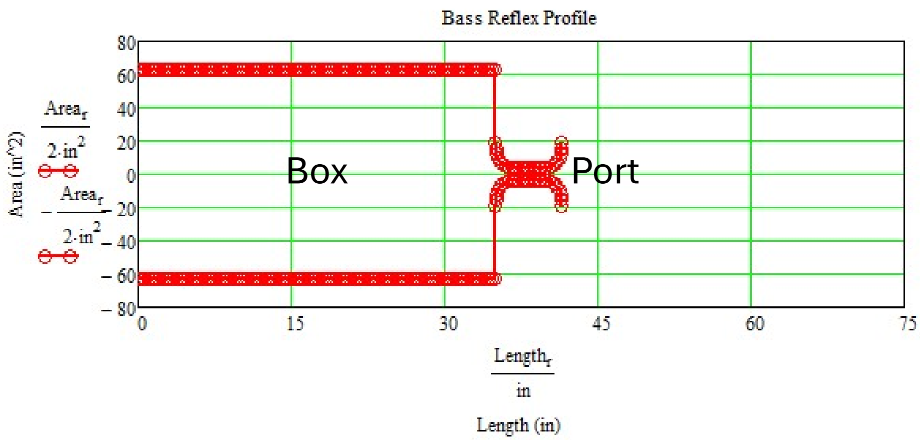
Volume Velocity and Pressure Profiles in the BR Enclosure at the Tuning Frequency - Rounded Port

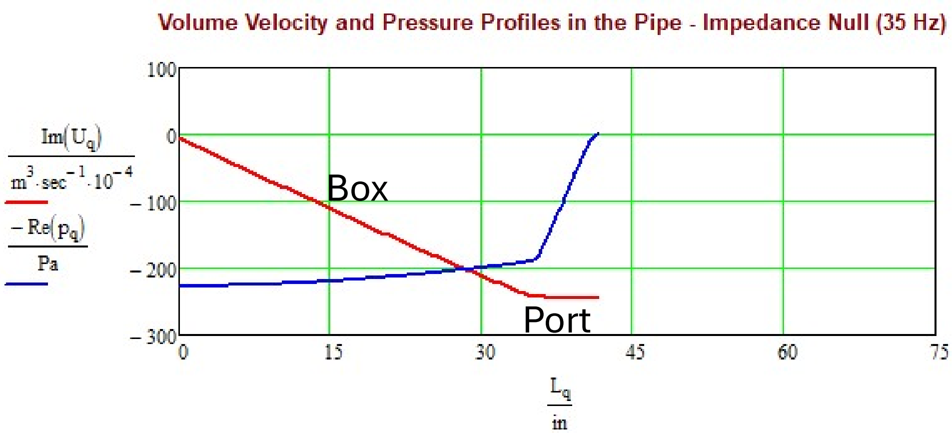




To improve the straight port's performance, and increase the linear output, two options are available. The diameter of the port can be increased to reduce the RMS velocity but at the expense of additional length. Or another more common method is to use higher tech ports with tapered or rounded ends.

In the plots at the left, a radius is applied to each end of the previously used straight port while keeping the length the same. The tuning frequency increases from 32 Hz to 35 Hz, not too surprising, but in general the plotted BR SPL and electrical impedance results look pretty much the same as those shown on slide 5.



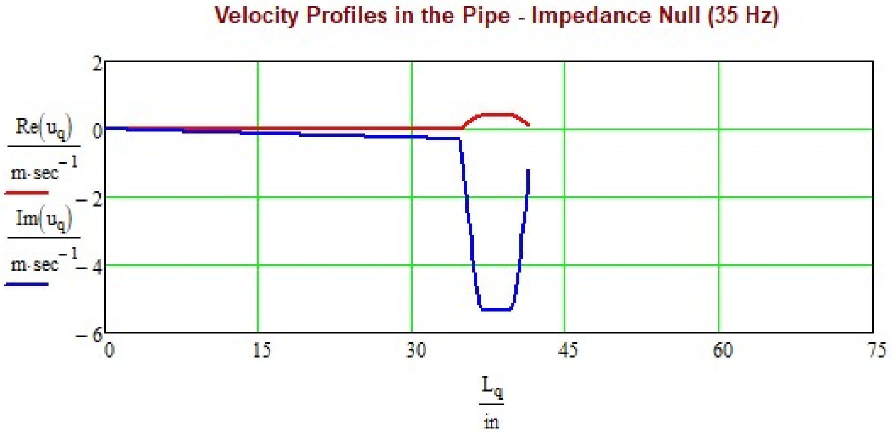


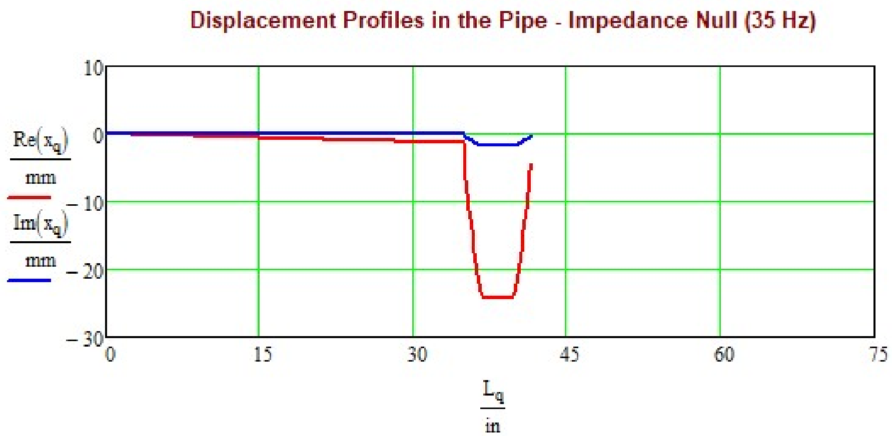
Compared to the results for the straight port, slide 6, the shape and magnitudes of the RMS pressure (red) and RMS volume velocity (blue) look very similar. But if you look closely a more gradual transition is seen at the entrance and exit of the port due to the rounded geometry.

All ports will experience similar boundary conditions. They can be mitigated by increasing the port cross sectional area and length or by applying flared/rounded geometries at the entrance and exit. But at some input power level, undesired noises will still be created.

Ports in BR or ML TL enclosures see a large oscillating pressure and a sudden change in oscillating volume velocity at the entrance from the box. There is also a significant pressure gradient along the length of the port. At the exit into the room the oscillating pressure is very small but there is still a sudden change in the local oscillating volume velocity as the sound waves radiate out into the room.

Velocity and Displacement Profiles in the BR Enclosure at the Tuning Frequency - Rounded Port

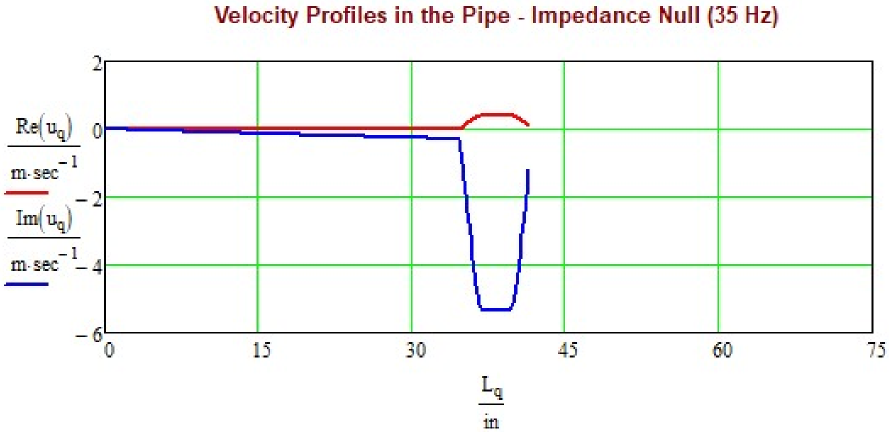


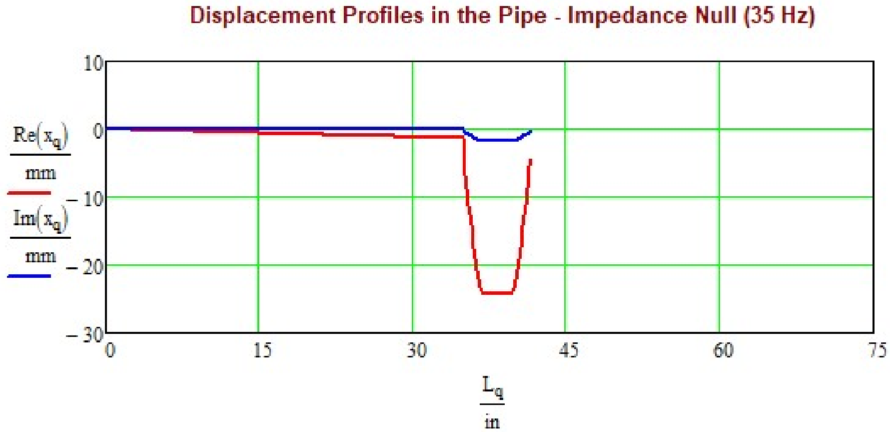


The RMS velocity and RMS displacement in the body of the port are the same as the previous results seen on slide 8. Real (red) and Imaginary (blue) curves are shown representing magnitude and phase (which again is almost zero). What is different is the more gradual transition from the inside of the box into the port and at the open end of the port out into the room.

The improved performance of this type of port is well documented. But if the RMS velocity and RMS displacement are about the same in the middle length of the port, the improved performance must be due to the less severe end effects from the air moving in and out of the rounded ends of the port.

The assumed metric on slide 2 is probably not the correct limit to impose for this style of port design, the speaker can accept more input power before the port behavior becomes nonlinear.



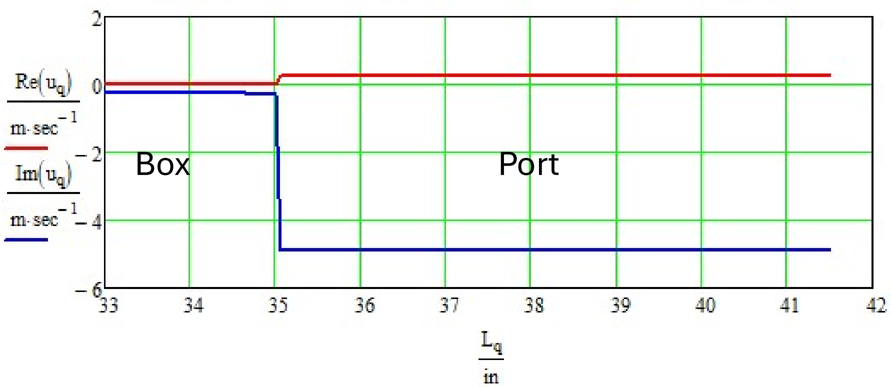


AES Preprint 4661 : Reduction of Bass-Reflex Port Nonlinearities by Optimizing the Port Geometry by N.B.Roozen, J.E.M. Vael, and J.A.M. Nieuwendijk arrives at similar results but in a much more rigorous analysis.

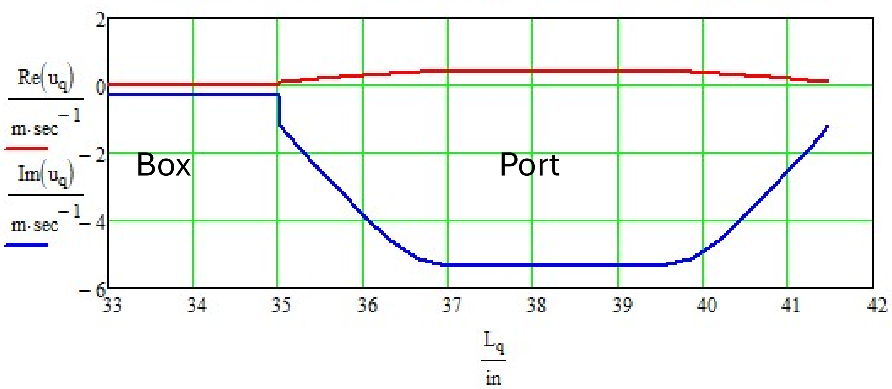
Extrapolating a little. The cross-section size, shape, and entrance/exit profiles of a port will determine at what input power it will start to become nonlinear and produce objectional noises. It does not appear that the velocity (and calculated Reynolds number) in the main body of the port tube leads directly to turbulence and additional noise artifacts. I have always struggled with the assertion that turbulent flow exists in the oscillating air column in a port. There is no net air flow in a loudspeaker. The entrance and exit geometries of the port appear to be the driving variable in port design. Using the metric from slide 2 is probably conservative for ports designed by 1D distributed or lumped parameter simulations.

Comparison of Velocity Profiles in a Straight Port and One with Rounded Entrance and Exit Profiles

Velocity Profiles in the Straight Pipe - Impedance Null (32 Hz)



Velocity Profiles in the Rounded Pipe - Impedance Null (35 Hz)

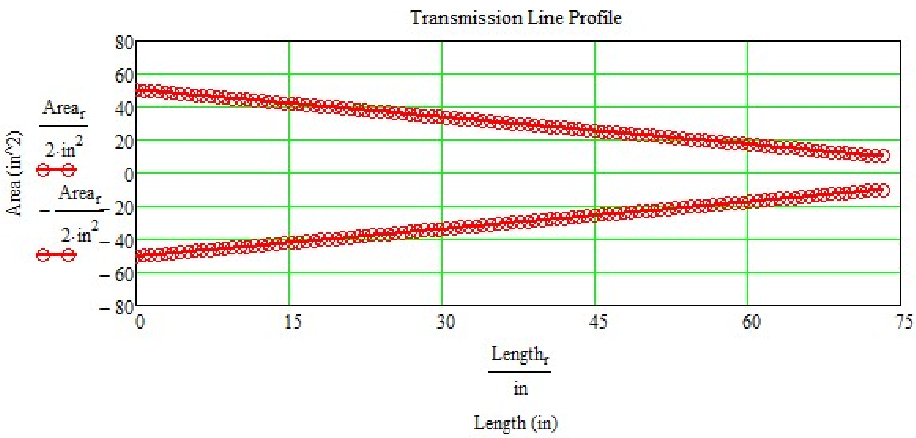


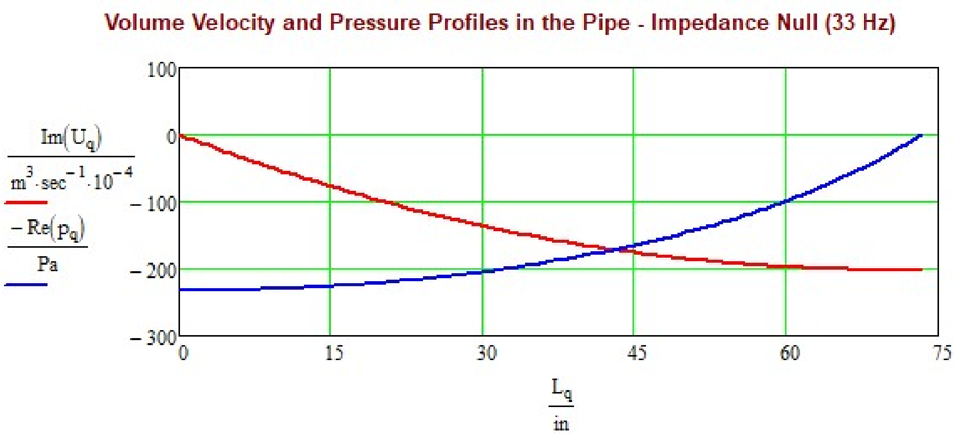
Taking a closer look at the RMS air velocity in the straight port (top plot at left) and the port with rounded ends (bottom plot) shows that the velocity in the center of the port is constant and almost the same, the big differences are at the ends. There will always be a sudden change in velocity at the joint between the box and the port due to the area change at this location.

The step change is much smaller with the rounded ends and the transition to the velocity in the center of the port tube is gradual. The end effects are much less severe for the port with the rounded ends.

I am not sure what metric to apply to the port tube with the rounded ends, but it is not surprising to find that it will take more input power to produce a nonlinear and noisy output compared to the simple straight port.

Volume Velocity and Pressure Profiles in the TL Enclosure at the Tuning Frequency

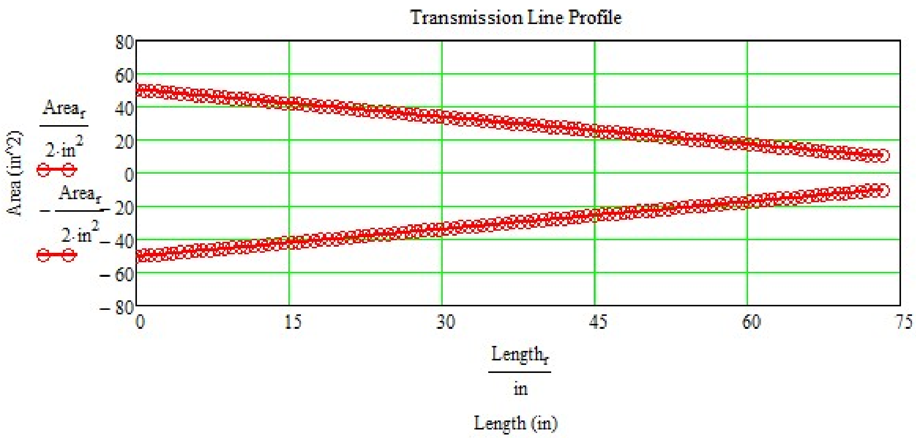


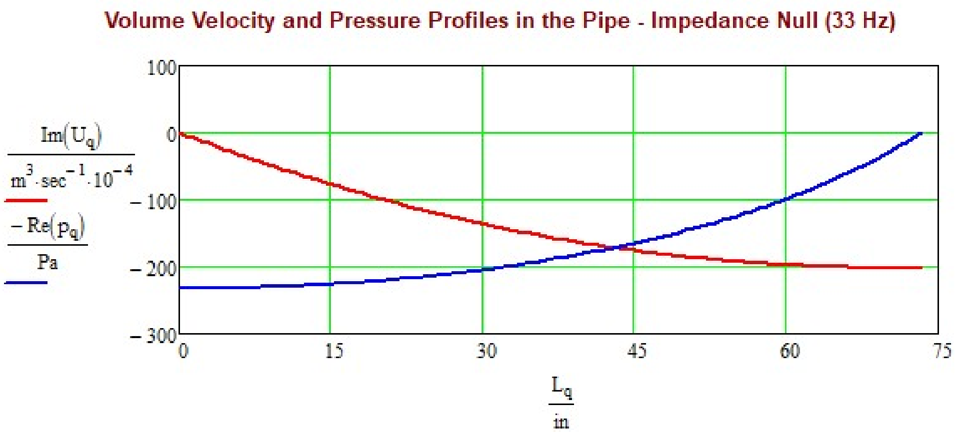


At left are plots showing the geometry and the RMS pressure p (blue) and RMS volume velocity U (red) along the length of the equivalent classic TL enclosure.

Comparing the RMS pressure and RMS volume velocity profiles of the original BR with a straight port, the same BR with a port that has rounded ends, and the TL the pressures at the closed ends and the volume velocities at the open ends are all about the same value. The difference is the smooth monotonic distribution of RMS pressure and RMS volume velocity along the length of the TL compared to the lumped parameter style of profiles in the BR designs.

In terms of cross-sectional areas of the open ends, the rounded end port is the biggest almost twice the TL's open end, while the straight port is the smallest about one third of the TL's open end.



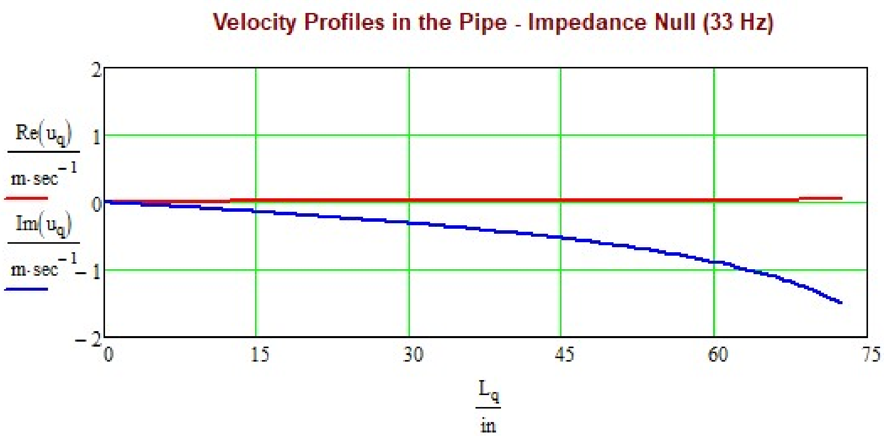


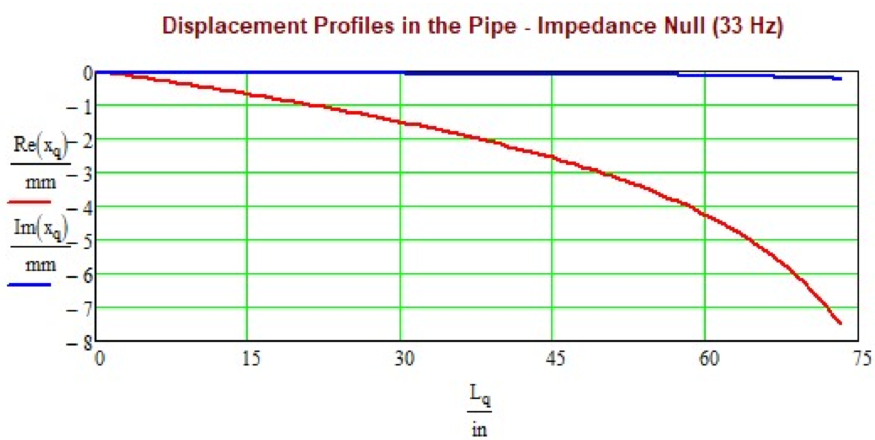
The RMS pressure at the closed end, on the back of the driver's cone, is 233 Pa which is equivalent to 141 dB. This corresponds to an RMS force on the driver's cone of 1.32 lbf, enough to stop the cone's motion at 33 Hz as seen in the right column's middle plot on slide 5, same as the BR result.

For comparison at 33 Hz, the SPL/m/2.8284 is 92.1 dB corresponding to an RMS pressure of 0.805 Pa and RMS displacement of 0.933 x 10^{-2} mm almost the same values as the BR design. This is what your ear picks up as sound at 1 m on the woofer axis. At the open end of the TL, assuming a port length equal to the enclosure's wall thickness, the RMS pressure driving the volume velocity is only 7.08 Pa, over 30 times less than both BR enclosures.

The volume velocity starts at zero at the closed end and decreases like a quarter sine wave attaining a maximum value at the open end. The pressure profile is a maximum at the closed end and follows a quarter cosine wave ending at zero at the open end. No sudden changes in slope so no end effects are generated, potentially no undesirable noise.

Velocity and Displacement Profiles in the TL Enclosure at the Tuning Frequency



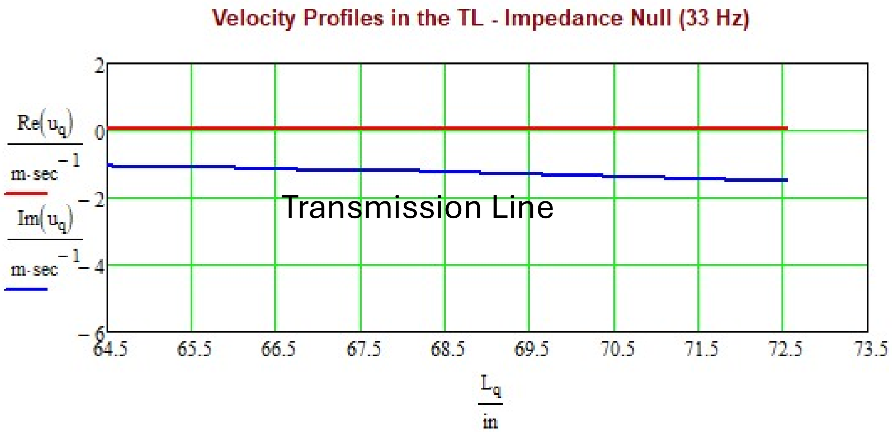


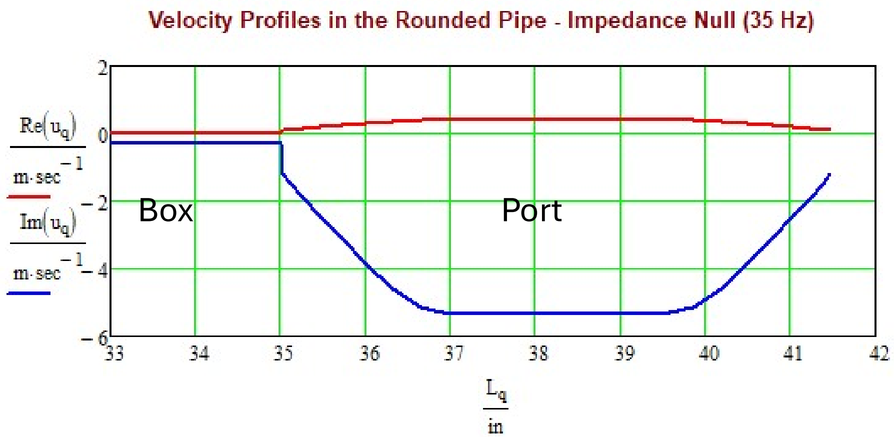
Dividing the volume velocity plot by the cross-sectional area produces the velocity plot, top plot. Integrating the velocity plot with respect to time, dividing by frequency, yields the displacement in the bottom plot. Real (red) and Imaginary (blue) curves are shown representing magnitude and phase (which is almost zero). These are both still RMS values at 33 Hz.

Again, you can drive any speaker to distortion with enough input voltage. In this example the RMS velocity is about 1.5 m/sec with an RMS displacement of 7.5 mm at 2.8284 volts (1 watt into 8 ohms) input. These values are significantly lower than the BR with a straight port results.

Increasing the voltage by a factor of 11 (121 watts at 33 Hz), the SPL at 1 m rises to 113 dB with an RMS velocity of 17 m/sec and an RMS displacement of 83 mm at the open end of the TL. This greatly exceeds the limitation imposed by the velocity metric on the BR port designs.

Comparison of Velocity Profiles in a Transmission Line and a Port with Rounded Entrance and Exit Profiles





Taking a closer look at the RMS air velocity in the classic TL (top plot at left) and the BR with a rounded port (bottom plot) shows that the velocity in the center of the port is significantly higher than at the open end of the TL. The TL does not produce any step changes, high local oscillating pressures, or steep gradients anywhere along the length. No discontinuities are seen like in the BR enclosure simulations.

I am not sure what metric for the RMS velocity should be apply to the open end of the classic TL, but it is obvious that the potential for higher output without any noises being generated is better with the TL geometry. The output for the TL enclosure should not be the limiting factor in any low frequency design, the driver's linear displacement X_{max} or voice coil thermal capacity would probably be limiting the performance.

Conclusions

“Every time I set up a transmission line I hear something I don't hear from conventional ported boxes, a quality of bass reproduction that is unique in its lightness and ease of reproduction of bass notes.”

I borrowed that quote from the referenced Troels Gravesen’s Ekta-TL design. I think it describes perfectly what has always drawn me to TL speaker designs.

In the three studies I have presented, the simulated bass behavior of a classic TL is superior, cleaner, and less resonant compared to the two BR ported systems. The lack of a step change in cross-sectional area in a classic TL enclosure eliminates a large oscillating pressure, steep pressure gradient, and step change in oscillating velocity and displacement just upstream of the open end. Both the BR and the ML TL styles of enclosure suffer from these problems. The classic TL has a much smoother pressure and velocity profile along its entire length right up to where sound exits the terminus and enters the listening room.

While you can juggle the port size, length, and geometry in a BR or MLTL so that it performs and is not limiting up to a specific input power requirement, the classic equivalent TL is a much easier design to eliminate unwanted end effects and resulting noises at its terminus. The TL tolerates a much higher input power compared to the equivalent BR enclosure. The classic TL enclosure is just a more robust speaker design for producing bass output around the enclosure’s tuning frequency.

Ref : Troels Gravesen’s ScanSpeak Ekta-TL page http://www.troelsgravesen.dk/Ekta-TL.htm